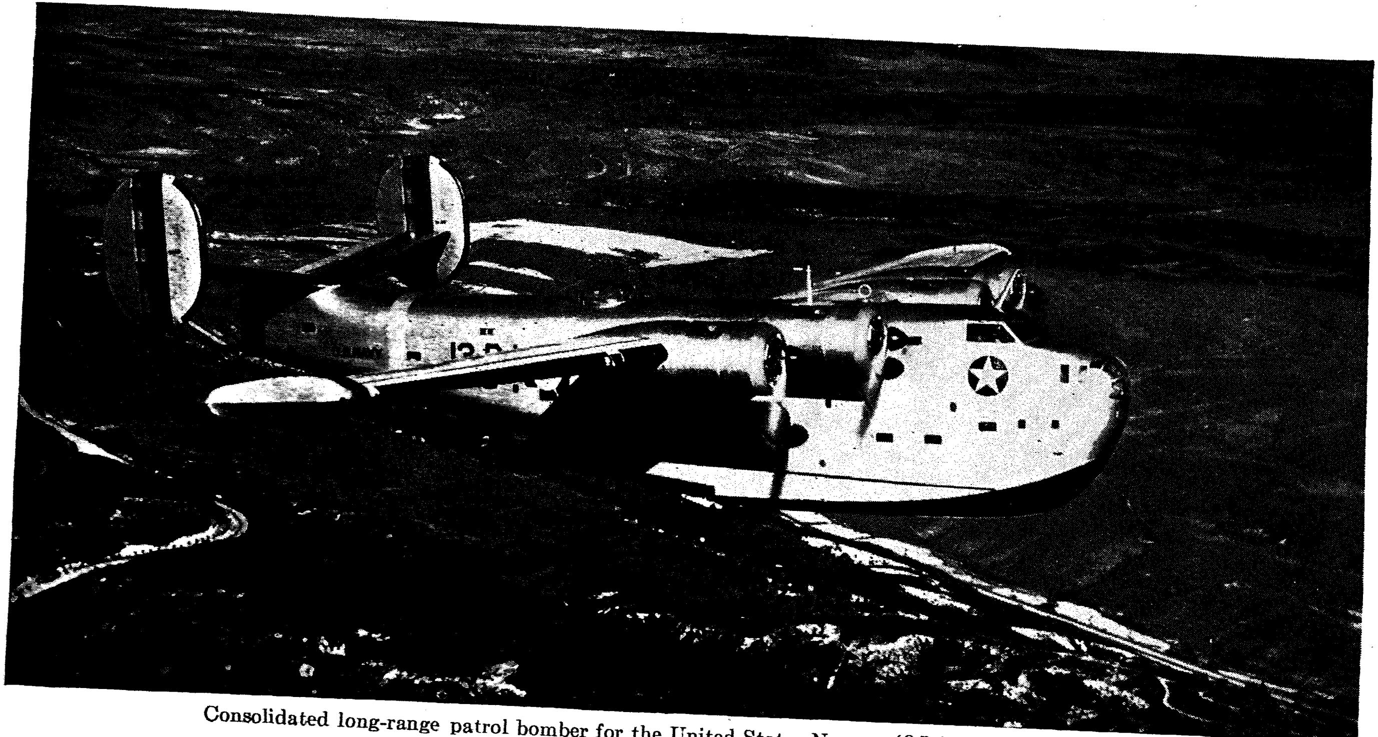

Consolidated long-range patrol bomber for the United States Navy. *(Official photograph, U.S. Navy.)*

(Frontispiece.)

INTRODUCTION

to

AIRCRAFT DESIGN

BY

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INTRODUCTION TO AIRCRAFT DESIGN

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PREFACE

The purpose of this book is to bridge the gap between the field of aeronautical engineering and airplane design and the other professional fields of engineering, architecture, and general design. The material originated in a course conducted by the University of California as part of its Engineering, Science, and Management Defense-Training Program which was designed to train engineers and draftsmen from civilian industries to fit into the aircraft industry during the national emergency. The work of this course was so successful that an immediate demand arose for a reference book based on it.

Since its inception, this type of training has been found to apply both to men coming directly from engineering colleges and universities without the benefit of any industrial experience and to men with a wide practical industrial experience and no engineering training. This volume is addressed in its present form to all engaged in the training of engineering and drafting personnel for the aircraft industry and its associates, the vendors of purchased equipment, subassemblies, and parts.

The field of engineering activity covered by the book is complete insofar as military-aircraft design is concerned; performance, power plants, control surfaces, fixed equipment, electrical equipment, and hydraulics are discussed at length with a view to their design and installation in the aircraft. The basic airplane structural design is covered in chapters on wing structure, fuselage and hull, landing gear, stress analysis, materials, and weight analysis. Involving most of these fields, a discussion of the activities of a general design group, contract administration, and testing groups is included. On the whole, the book will cover the activities of any aircraft-engineering department though it is based upon lectures presented by group engineers of the Consolidated Aircraft Corporation. This is true because, although highly specialized, airplane design is limited by the specifications and requirements of the customer and further limited by the parts and materials available.

No attempt has been made to explain or enter into basic fundamentals of engineering or physics, for an understanding of these is a prerequisite to the training of any draftsman or engineer. The aim has been to provide the additional amount of information to fit the man with general training and background into the specialist's job. This work will also be useful to those formerly engaged in nondefense production who now find themselves producing parts for military aircraft without any single source of information on the general aspects of the airplane as a whole.

Careful study of this book will reveal the functions and purposes of the aircraft and its components from the designer's viewpoint. A consideration of the problems of weight, efficiency, cost, and production has been included so that the seemingly complicated airplane assembly may be analyzed by functional parts or groups and the reasons for the choice of their design determined.

The author wishes to express his gratitude to the originators of the outlines and material: R. L. Bayless, Aerodynamics Engineer; S. D. Whitaker, Power Plant Engineer; R. L. Goodyear and J. Holston, Control Surface Engineers; J. L. Wainwright, Wing Engineer; L. O. Cederwall, Hull Engineer; W. E. Eldred, Landing Gear Engineer; P. A. Carlson, Fixed Equipment Engineer; C. F. McCabe and G. Sylvester, Electrical Engineers; C. B. Livers and W. S. Saville, Hydraulics Engineers; M. R. Rosenbaum and C. Gerber, Stress Engineers; W. A. Schurr and B. M. Novak, Materials Engineers; S. H. Avery, Weights Engineer; R. C. Hager, General Group Engineer; and K. R. Jackman, Test Engineer, all of the Consolidated Aircraft Corporation; to the University of California for its cooperation; and to the Consolidated Aircraft Corporation for the illustrations.

THOMAS P. FAULCONER.

SAN DIEGO, CALIF.,
October, 1942.

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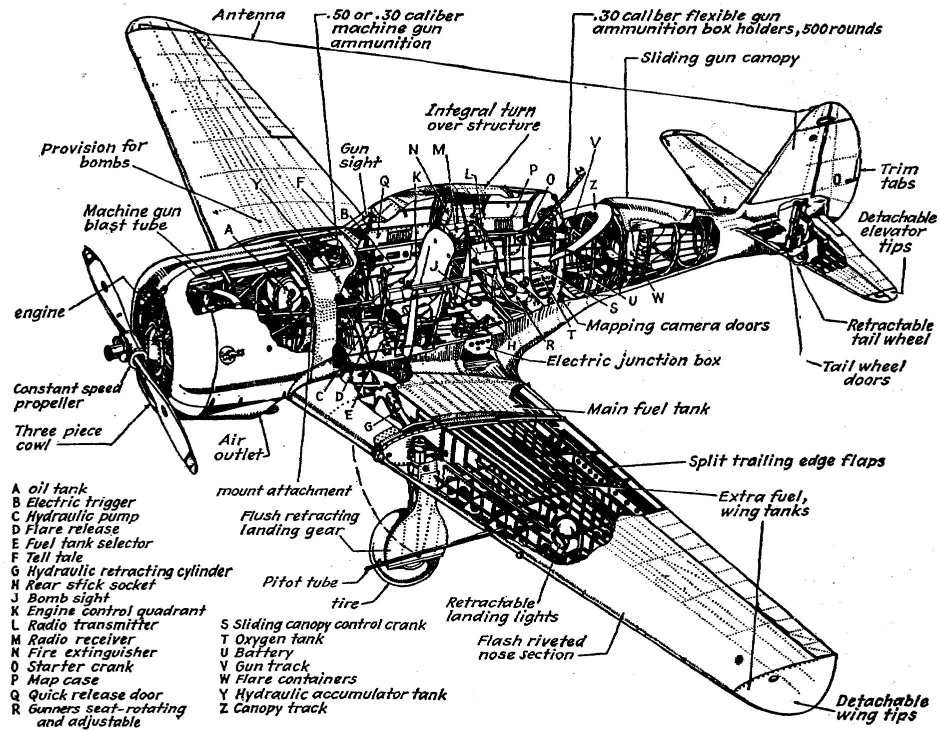
INTRODUCTION

During the tremendous expansion of the aircraft industry in the last two years the supply of experienced engineers and draftsmen has been virtually exhausted. Therefore the breaking-in time required for new men in aircraft-engineering departments has become noticeably longer. The Consolidated Aircraft Corporation has tried to shorten this time by helping the new men fit into the picture as quickly and easily as possible. This has been accomplished by means of supplementary evening-school training and more recently by organized classroom training during working hours to train men freshly graduated from engineering colleges or transferred from the drafting table in other industries. However, neither of these means meets the demand, and for such personnel as are trained by the former method some standard reference book of procedures, systems, and standards is necessary.

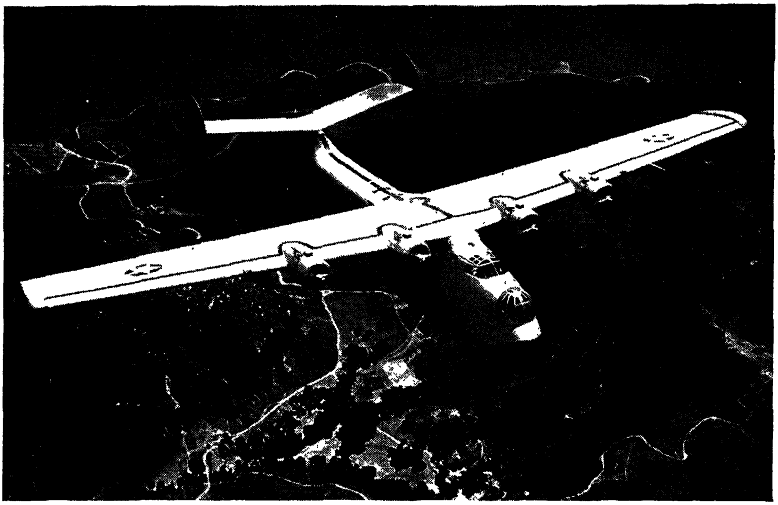
Thomas P. Faulconer was instrumental in bringing the organized training of engineering and drafting personnel to the Consolidated Aircraft Corporation under the University of California sponsorship. Since 1935, he has had experience as an engineer in several of the design groups, which enabled him to compile and enlarge the data of the engineers in charge of these groups into an accurate account of design procedure from preliminary proposal to finished airplane.

This volume should prove valuable not only to members of the engineering staff but also to those in all departments having to do with engineering drawings. Men in the production and tool-design departments have found material of this nature useful in interpreting engineering drawings and in determining the reasons behind the design. Men in the shop may discover in it an index to the vast amount of knowledge, data, research, and design work that must go into the airplane.

H. A. Sutton,
Chief Engineer,
Consolidated Aircraft Corporation.



Nomenclature of a typical airplane.



Consolidated long-range patrol bomber. *(Official U.S. Navy Photograph.)*

CHAPTER I

AERODYNAMICS AND PRELIMINARY DESIGN

Not long ago the aircraft industry consisted of small organizations in which the engineering departments were made up of 5 to 10 men. Little thought was given to aerodynamic refinement, for power plants had insufficient power to propel the craft at high enough speeds to warrant much concern in this respect. Weight was the major consideration, for poor weight control had doomed some airplanes never to leave the ground or to be grounded at any load condition other than weight empty. Very great sacrifices were made in drag so that the weight might be kept down to usable values. Radial air-cooled engines were uncowled because no method had been found to cool these engines satisfactorily other than by exposing them freely to the air stream. Landing gears were not retracted, the weight sacrifice being prohibitive and the mechanism too complicated. High-lift devices and tricycle landing gears had not been perfected, and wing loadings were consequently very low. All this required the use of very large wing areas to support the weight.

In contrast, present-day airplanes have reached a stage of development in which the old ideas are entirely obsolete. Aerodynamic refinement now "pays dividends" on some designs regardless of the cost in weight and the added complication of design. This stage has been attained only through willingness to accept these penalties in order to gain 2 to 3 m.p.h. or even 1 m.p.h. in many cases. Notable advances in reducing drag by large amounts have been effected by the cowling of radial engines, the retraction of landing gears, and the elimination of struts and wires by cantilever support. These came naturally in due course of time; but the 1 m.p.h. here and the 1 m.p.h. there, which, although negligible separately, add up to 20, 30, or even 40 m.p.h., are the result of painstaking design and refinement.

The problem, therefore, appears simple. The airplane should be "cleaned up" to the maximum extent. At this point the other extreme is reached, and we are forced to return once more to other than aerodynamic considerations. For we must accommodate not the ideal power plant but the one that is available; we must have proper visibility with consequent windshield protuberances; we must incorporate gun turrets and bomb bays in military designs; most important of all if the manufacturer is to survive, we must reduce the complexity of design to an extent where the airplane is easy and inexpensive to build.

Thus we are confronted with a vicious circle in which careful and well-considered compromises in respect to weight, aerodynamic refinement, and design are necessary if we are to obtain the maximum usefulness of the design. One manufacturer may therefore delete the more expensive process of flush riveting in order to speed up and reduce the cost in production, whereas his competitor may go to the extreme in aerodynamic refinement and flush-rivet everything. The former will in all probability sell more airplanes.

In the large organizations of present-day aircraft plants, there must of necessity be a number of groups who are specialized in their particular lines. The time is past when 5 or 10 men know all the details and hold the whole design in the palm of their hand, so to speak. It is true, of course, that aircraft organizations are still relatively small as compared with some other industries and that one or two men in most cases make the decisions on all major items. The research, tests, and studies on which these decisions

are based are conducted, however, by specialized groups. Each strives for perfection in its particular line, the ideal organization resulting when each group is sufficiently familiar with all other groups for the design to proceed with speed and with no interference or controversy.

The routine work of the aerodynamics group is briefly discussed in this chapter. Some of the simpler fundamental conceptions in aerodynamics are first outlined in order to establish a basis for further discussion.

FUNDAMENTAL CONCEPTIONS IN AERODYNAMICS

The fundamental conceptions are of major importance in aerodynamics. (1) The conception of relative motion states that the forces acting on a body in motion in a stationary fluid are the same as those acting on a body when the body remains stationary and the fluid moves past it. (2) The fluid pressures that act on the body and that cause the forces have nothing to do with compression in most cases. These forces arise primarily from causes accounted for by Bernoulli's theorem. Compressibility of the air must be taken into account at speeds above 250 to 300 m.p.h., but this effect need not be discussed here.

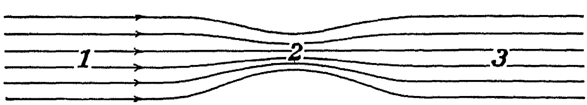


FIG. 1.—Streamline flow through a constricted tube.

The first conception is recognized immediately in the application of wind-tunnel test data to prediction of full-scale flight characteristics. In this case a model is supported in a moving air stream to simulate an airplane flying in stationary air. The second conception requires further explanation in which it is convenient to conceive of airflow as a series of streamlines.

Static and Dynamic Pressure.—These streamlines may be thought of as horizontal straight lines, in an undisturbed flow, and may be given any convenient spacing in the representation of a flow. Consider first the flow in a tube of circular cross section with a necked-down portion at the center (Fig. 1). Positions in the tube are designated by (1), (2), and (3).

We see that the flow is identical at the two ends, with identical streamline spacing. The area of the two ends is the same, and it

is evident that the velocity at the two ends must be the same since the same quantity of air must leave at (3) that enters at (1). At the center, however, the streamline spacing is much closer since the same number of streamlines must pass through this area that passed through the larger area, or we may say that the same quantity of air must pass through this area that passed through the larger area. Therefore, the velocity at point (2) must be greater than at the two ends.

Bernoulli's theorem states that the total pressure in a flow must be the same at all points; we may liken this to the conception of the conservation of energy. In the above flow there are the two types of pressure, static and dynamic. The static pressure is represented by P, in pounds per square foot, and the dynamic pressure by $\frac{1}{2}\rho V^2$, also in pounds per square foot.

In this expression, ρ is the mass density of the fluid in slugs per cubic foot and V is the velocity in feet per second. (Any other consistent system of units may be used, but it is convenient to use only the foot-pound-second system here.) Therefore, by Bernoulli's theorem and neglecting friction losses, which if in existence would be dissipated as heat,

$$P_1 + \tfrac{1}{2}\rho_1 V_1^2 = P_2 + \tfrac{1}{2}\rho_2 V_2^2 = P_3 + \tfrac{1}{2}\rho_3 V_3^2$$

As stated before, for most cases air may be considered as incompressible and therefore, if we are considering a flow of air in this tube,

$$\rho_1 = \rho_2 = \rho_3 = \rho$$

and

$$P_1 = P_3 \qquad \text{and} \qquad V_1 = V_3$$

since the conditions at (1) and (3) (Fig. 1) are seen to be identical. Also, [cross-sectional area at (1)] $\times V_1$ = [cross-sectional area at (2)] $\times V_2$ for continuity of flow since (area)(velocity) gives the quantity of air flowing per unit of time. Therefore, we may write

$$V_1 = \frac{A_2}{A_1} V_2$$

where A_2 = cross-sectional area at (2) and A_1 = cross-sectional area at (1). By substituting this in the above equation, we have

$$P_1 + \frac{1}{2}\rho\left(\frac{A_2}{A_1}\right)^2 V_2^2 \qquad P_2 + \frac{1}{2}\rho V_2^2$$

from which

$$V_2 = \sqrt{\frac{P_1 - P_2}{\frac{1}{2}\rho\left[1 - \left(\frac{A_2}{A_1}\right)^2\right]}}$$

Therefore if we were to install pressure gauges at points (1) and (2), so that only the static pressure is measured, it would be possible to determine $(P_1 - P_2)$ and, knowing the density of the air and the dimensions of the tube, V_2 could be computed

For example, assume

$$A_1 = 3 \text{ sq. ft.}, \qquad A_2 = 2 \text{ sq. ft.}$$
$$P_1 - P_2 = 3 \text{ lb./sq. ft.}$$
$$\rho = 0.002378 \text{ slugs/cu. ft.}$$

for National Advisory Committee for Aeronautics (N.A.C.A.) standard air at sea level. Then

$$V_2 = \sqrt{\frac{3}{\frac{0.002378}{2}\left[1 - \left(\frac{2}{3}\right)^2\right]}} = 67 \text{ ft./sec}$$

and, from the foregoing relation of $V_1A_1 = V_2A_2$,

$$V_1 = 67\left(\tfrac{2}{3}\right) = 45 \text{ ft./sec.}$$

We therefore see that a reduction in pressure of 3 lb. per sq. ft. definitely establishes that the velocity at (1) is 45 ft. per sec. and the velocity at (2) is 67 ft. per sec. Similarly, if the pressure reduction is 30 lb. per sq. ft., $V_2 = 212$ ft. per sec. and $V_1 = 142$ ft. per sec.; for 300 lb. per sq. ft. pressure reduction, $V_2 = 670$ ft. per sec., and $V_1 = 450$ ft. per sec.

Summing up, we have

Pressure difference, lb./sq. ft.	Pressure difference, lb./sq. in.	V_2, ft./sec.	V_1, ft./sec.	$V_2 - V_1$, ft./sec.
3	0.021	67	45	22
30	0.208	212	142	70
300	2.08	670	450	220

This shows that relatively small pressure changes give rise to fairly large velocity changes.

To clarify the conception of static and dynamic pressure we may conceive of static pressure as the pressure in a tank in which there is no flow or we may think of the static pressure in the atmosphere where under standard conditions a barometer will read 29.921 in. Hg which is equivalent to 2,116.4 lb. per sq. ft., or 14.7 lb. per sq. in. Dynamic pressure arises entirely from the impact of fluid particles and can exist only where a velocity is present. For example, if we hold a flat plate perpendicular to an air stream, a force is exerted on the plate owing to the impact of the air on the plate. Also, if a tube is held parallel to an air stream as shown in Fig. 2, a pressure is built up in the tube that is equal to $\frac{1}{2}\rho V^2$ and that may be read on a U tube, or gauge. If it is assumed that the U tube contains water, then

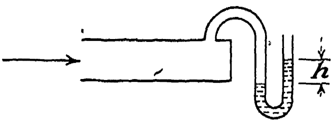


FIG. 2.—Measurement of dynamic pressure by means of a U tube.

$$\tfrac{1}{2}\rho V^2 = 5.204h$$

where h is in inches of water.

The familiar air-speed head used on airplanes for determining air speed is just such a tube, with the addition of a static-pressure

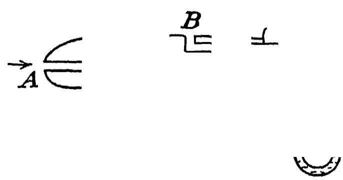


FIG. 3.—Air-speed head.

connection for the U tube instead of the end being left open to the atmosphere in the cockpit or wherever the instrument is located. The pressure $\frac{1}{2}\rho V^2$ is exerted at A (Fig. 3), whereas only the static pressure in the atmosphere is exerted at B. Obviously, the static pressure is also present at A, so that at A we have a total pressure of $P + \frac{1}{2}\rho V^2$ and at B only the static pressure P. Connecting these two lines to the U tube, which may contain water or alcohol, gives a difference in pressure of h in. water which is equal to the total pressure minus the static pressure, or $h = \frac{1}{2}\rho V^2$. If the

pressure altitude of flight and the air temperature are known, ρ may be computed and V therefore determined.

For example, let

$$h = 20 \text{ in. water}$$
$$= 20 \times 5.204 = 104.08 \text{ lb./sq. ft.}$$

Pressure altitude of flight = 10,000 ft.
Air temperature = $-4.8°$C.

$$\rho = 0.7384 \times 0.002378 = 0.001755 \text{ at } 10{,}000 \text{ ft.}$$

From N.A.C.A. atmospheric tables,

$$V = \sqrt{\frac{104.08 \times 2}{0.001755}} = 344 \text{ ft./sec., or } 235 \text{ m.p.h.}$$

Dimensional Homogeneity.—It is well to introduce at this point another conception, that of dimensional homogeneity, which is very useful in deriving and evaluating many equations and expressions. It may be used in the preceding discussion to show that the dimensions of the expression for dynamic pressure, $\frac{1}{2}\rho V^2$, are in pounds per square foot just as the static pressure is in pounds per square foot. There are three basic dimensions, length (L), force (F), and time (T). This was previously implied when the foot-pound-second system of units was mentioned. For the expression $\frac{1}{2}\rho V^2$, we have

$\frac{1}{2}$, which is merely a numerical constant and is dimensionless.

ρ, which is in slugs per cubic foot, *i.e.*, mass per cubic foot. This is pounds per cubic foot divided by g, the acceleration due to gravity.

g is in feet per second per second and V is in feet per second. Therefore we have

$$\left(\frac{F}{L^3}\right)\left(\frac{T^2}{L}\right)\left(\frac{L^2}{T^2}\right)$$

which reduces to

$$\frac{F}{L^2} = \text{lb./sq. ft.}$$

The principle of dimensional homogeneity states that both sides of an equation must have the same dimensions for the equation to be valid.

Basic Force Equations.—The application of this principle of dimensional homogeneity leads to the derivation of the basic force equations used in performance analysis and wind-tunnel testing. Osborne Reynolds, an English engineer and physicist, laid the foundation of all modern fluid mechanics during the latter part of the nineteenth century when he established the fact that the force exerted on a body by a fluid in motion is a function of the length of the body, the velocity of the fluid past the body, and the physical characteristics of the fluid. This may be written as

$$\text{Force } (F) = f(L, V, \rho, \mu)$$

in which ρ and μ represent the physical characteristics of the fluid.

The physical characteristics of the fluid are definitely established by the density and the viscosity.

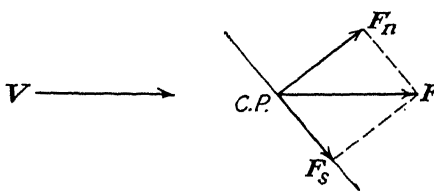


FIG. 4.—Forces acting on a flat plate inclined to the air stream.

The density ρ is the weight of the fluid in pounds per cubic foot divided by g, the acceleration due to gravity, and is usually expressed in slugs per cubic foot. (ρ is more correctly called the *mass density*.)

The viscosity of the fluid is the property by which it clings to a body as oil sticks or clings to a bearing. Oil of S.A.E. 50 viscosity is much thicker and more resistant to motion than oil of S.A.E. 10 viscosity. Similarly, the viscosity of air may be represented as follows:

Consider a plate inclined to an air stream as in Fig. 4. The impact of the particles of air against the plate will produce a force F acting at the center of pressure (c.p.). This force may be resolved into a normal force F_n and a shearing force F_s. Newton's law, which has been verified often by experiment, states that this shearing force on the plate, per unit of area, is

$$F_s/\text{sq. ft.} = f_s = \mu \frac{du}{dy}$$

where u is the tangential component of the velocity at a distance y from the surface of the plate and μ is the coefficient of viscosity. Hence, by dimensional analysis,

$$\mu = \frac{f_s\,dy}{du} = \left(\frac{F}{L^2}\right)\left(\frac{T}{L}\right)L = \text{lb.-sec./sq. ft.}$$

Therefore, in the original force equation

$$F = f(L, V, \rho, \mu)$$

we have, by summing up all the forces exerted on the body by the fluid,

$$F = \Sigma k L^a V^b \rho^c \mu^d$$

where k is a constant of proportionality and the exponents have values to make the equation dimensionally correct. By dimensional analysis, we have

$$\begin{aligned} F &= L^a \left(\frac{L^b}{T^b}\right)\left(\frac{F^c}{L^{3c}}\right)\left(\frac{T^{2c}}{L^c}\right)\left(\frac{F^d T^d}{L^{2d}}\right) \\ &= L^{(a+b-3c-c-2d)} F^{(c+d)} T^{(2c+d-b)} \end{aligned}$$

and

$$a + b - 4c - 2d = 0 \qquad (1)$$
$$-b + 2c + d = 0 \qquad (2)$$
$$c + d = 1 \qquad (3)$$

which gives three equations with four unknowns. We can therefore solve for three of the unknowns in terms of the fourth.

Subtracting Eq. (3) from Eq. (2) gives

$$\begin{aligned} -b + c &= -1 \\ b - c &= 1 \end{aligned} \qquad (4)$$

Multiplying Eq. (2) by 2 and adding the result to (1) give

$$a - b = 0, \qquad a = b \qquad (5)$$

We then let

$$c = x$$

from which

$$d = 1 - x$$
$$b = 1 + x$$
$$a = 1 + x$$

Placing these exponents in the original force equation gives

$$F = \sum kL^{1+x}V^{1+x}\rho^x\mu^{1-x}$$
$$= \sum \frac{kL^{x+1}V^{x+1}\rho^x}{\mu^{x-1}}.$$

Multiplying and dividing by $LV\rho/\mu$ gives

$$F = \left(\sum \frac{kL^{x+2}V^{x+2}\rho^{x+1}}{\mu^x}\right)\left(\frac{\mu}{LV\rho}\right)$$

and factoring out $(LV\rho/\mu)^x$ gives

$$F = \sum KL^2V^2\rho\left(\frac{LV\rho}{\mu}\right)^x\left(\frac{\mu}{LV\rho}\right)$$
$$= \sum kL^2V^2\rho\left(\frac{LV\rho}{\mu}\right)^{x-1}$$
$$= L^2V^2\rho\sum k\left(\frac{VL}{\nu}\right)^\eta$$

where $\eta = (x - 1)$ and $\nu = \mu/\rho$ which is designated as the kinematic viscosity and has the dimensions square feet per second. The term (VL/ν) is dimensionless.

If we arbitrarily let

$$\sum k\left(\frac{VL}{\nu}\right)^\eta = \frac{1}{2}C_D$$

and take the wing area as the representative dimension for (L^2), we have

$$F = \text{drag} = D = C_D S \tfrac{1}{2}\rho V^2$$

where S = wing area.

This is the basic drag equation in the form normally used. The significance of the $\frac{1}{2}$ in the term $\frac{1}{2}C_D$ is immediately evident when

we note that the final drag equation has the term $\frac{1}{2}\rho V^2$ which is merely the dynamic pressure, previously discussed.

The term C_D is dimensionless and depends on the term VL/ν which is called the Reynolds number in honor of Osborne Reynolds.

The force equation $F = CS\frac{1}{2}\rho V^2$ may be applied to any other force as well, if the representative coefficient C is used. It would appear that only the drag could be so represented since the force was originally conceived as a shearing or drag force depending on the viscosity of the fluid, however it was also shown that the viscosity enters only in the Reynolds number (R.N.) and is not part of the force equation. We may write, therefore,

$$\text{Lift} = L = C_L S \tfrac{1}{2}\rho V^2$$
$$\text{Side force} = C = C_S S \tfrac{1}{2}\rho V^2$$

in which according to our previous analysis C_L and C_S will be some function of the Reynolds number. The variations of these various coefficients with the Reynolds number is found experimentally in the wind tunnel.

The effects of these forces on the airplane are as follows:

Drag.—This retards the motion of the airplane and is positive when in the downstream direction. There must be a thrust in the opposite direction equal to the drag, for steady flight.

In evaluating the drag of the airplane, two distinct types of drag are present.

1. The parasite, or impact and frictional, drag on all parts of the airplane.

2. The induced drag, which may be considered as the drag induced by the lift.

The physical significance of the parasite drag is easily understood. Holding a flat plate perpendicular to an air stream gives rise to a drag, or downstream force, on the plate. This is a parasite-drag force. Parasite drag also arises from the frictional drag of the fluid on the body.

The induced drag cannot be fully visualized without further explanation which involves elaborate treatments in fluid mechanics variously described as the circulation theory, vortex theory, induced-drag theory, and potential-flow theory. Space does not allow consideration of any of these analyses; however a very elementary analysis based directly on Newton's law,

Force = (mass) (acceleration), gives many of the same results as the more elaborate treatments.

Lift.—This lifts the weight of the airplane for sustained flight. This lift acting at the center of pressure (c.p.) produces a pitching moment about the center of gravity (c.g.) of the airplane.

Moment.—This is represented by a force times a length, or

$$Fl = Ll = (C_L S \tfrac{1}{2}\rho V^2)l$$

The representative length L is usually taken as the mean aerodynamic chord (m.a.c.) of the wing in the case of pitching moment, and therefore we have the following:

Pitching moment.

$$\text{Pitching moment} = M = C_M Sc\tfrac{1}{2}\rho V^2$$

where C_M is the representative coefficient for pitching moment and c is the m.a.c. of the wing.

The pitching moment is balanced by the load on the tail which acts in a direction to counteract the pitching moment for steady flight.

Side force. This force is zero for a symmetrical airplane in unyawed flight. When yaw is introduced, a side force is built up and produces a yawing moment.

Yawing moment.

$$\text{Yawing moment} = N = C_N Sb\tfrac{1}{2}\rho V^2$$

where C_N is the representative coefficient for yawing moment and b is the wing span which is selected as the representative length for yawing moment.

Obviously a drag force acting at the wing tip could also produce a yawing moment. Therefore C_N represents a summation of all forces producing a yawing moment.

One more moment is produced by the various forces acting on the airplane.

Rolling moment.

$$\text{Rolling moment} = L = C_L Sb\tfrac{1}{2}\rho V^2$$

where C_L is the rolling moment coefficient.

This analysis of the forces exerted on an airfoil by an air stream that moves relative to the airfoil involves the major assumption

that the airfoil deflects a cylindrical stream of air the diameter of which is equal to the span of the airfoil, or wing.

Figure 5 shows the streamlines around an airfoil in a perfect fluid. In Fig. 5, V_1 is the velocity well forward of the airfoil

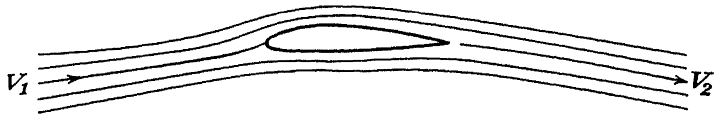


FIG. 5.—Streamline flow about an airfoil.

where the flow is undisturbed by the proximity of the airfoil. V_2 is the velocity well back of the airfoil; it is equal to V_1 but differs from V_1 in that it has been deflected downward from V_1 through an angle ϵ. This angle is called the *angle of down-wash.*

For small down-wash angles,

$$\Delta V = V\epsilon$$

where ϵ is in radians. Newton's law applied to a deflected air stream may be stated as follows:

$$\begin{aligned}\text{Force} &= \text{mass} \times \text{acceleration} \\ &= \text{mass} \times \left(\frac{V_2 - V_1}{\Delta t}\right) \\ &= m\,\Delta V\end{aligned}$$

where m is the mass of air deflected per unit of time and ΔV is the vectorial change of velocity. The force exerted on the airfoil by the deflected air stream is in a direction opposite to ΔV and

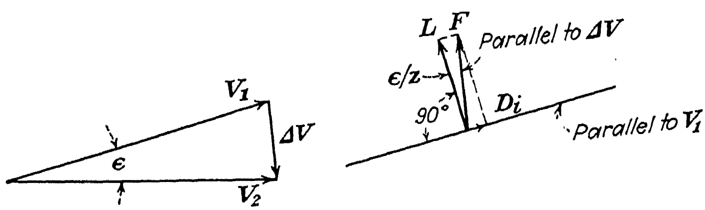


FIG. 6.—Forces acting on an airfoil.

may be represented as shown above (Fig. 6). F is the force, and L and D_i are its components in the direction of lift and drag relative to V_1. L is therefore the lift, and D_i is the induced drag.

The mass of air deflected per unit of time (or per second) is calculated based on the original assumption that the airfoil

deflects a cylindrical stream of air of diameter equal to the span of the airfoil.

For an airfoil of span b (Fig. 7), the area of the air stream is $\pi b^2/4$, and the mass of air flowing through this area per second is

$$m = \left(\frac{\pi b^2}{4}\right)\rho V$$

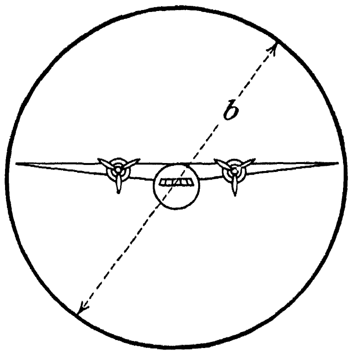


FIG. 7.—Area of disturbed air flow.

where ρ = mass density and V = velocity.

Substituting this and the relation $\Delta V = V\epsilon$ in $F = m\,\Delta V$ gives

$$F = \left(\frac{\pi b^2}{4}\right)\rho V^2\epsilon$$

For small down-wash angles,

$$\text{Force} = \text{lift} = C_L S \tfrac{1}{2}\rho V^2$$

from previous analysis. Therefore,

$$C_L S \frac{1}{2}\rho V^2 = \frac{\pi b^2}{4}\rho V^2\epsilon, \qquad C_L = \frac{\pi b^2}{2S}\epsilon \tag{6}$$

From Fig. 6,

$$D_i = L\left(\frac{\epsilon}{Z}\right)$$

Dividing by $S\frac{1}{2}\rho V^2$ gives

$$\frac{D_i}{S\frac{1}{2}\rho V^2} = \left(\frac{L}{S\frac{1}{2}\rho V^2}\right)\left(\frac{\epsilon}{Z}\right)$$

$$C_{D_i} = (C_L)\left(\frac{\epsilon}{Z}\right) = \left(\frac{\pi b^2}{2S}\right)\left(\frac{\epsilon^2}{Z}\right)$$

From Eq. (6),

$$\epsilon = \frac{2SC_L}{\pi b^2}$$

and

$$C_{D_i} = \left(\frac{\pi b^2}{4S}\right)\left(\frac{4S^2C_L^2}{\pi^2 b^4}\right) = \frac{C_L^2}{\pi(b^2/S)}$$

where b^2/S = aspect ratio = R. Therefore,

$$C_{D_i} = \frac{C_L{}^2}{\pi R}$$

or, multiplying by $S\frac{1}{2}\rho V^2$,

$$C_{D_i}S\tfrac{1}{2}\rho V^2 = \frac{C_L{}^2 S\frac{1}{2}\rho V^2}{\pi R}$$

and

$$D_i = \frac{L^2}{\pi b^2 \frac{1}{2}\rho V^2}$$

We have therefore developed the three basic force equations used in all performance analysis. Summarizing, we have

$$\text{Drag} = D = C_D S\tfrac{1}{2}\rho V^2 \qquad (7)$$

$$\text{Lift} = L = C_L S\tfrac{1}{2}\rho V^2 \qquad (8)$$

$$\text{Induced drag} = D_i = \frac{L^2}{\pi b^2 \frac{1}{2}\rho V^2}$$

or, as it is generally used in coefficient form,

$$C_{D_i} = \frac{C_L{}^2}{\pi R} \qquad (9)$$

Equations (7), (8), and (9) are usually memorized, their development being so laborious. All other equations used in performance analysis are developed easily from these three basic equations and need not be memorized.

We shall now see how these basic equations may be applied constructively to airplane design.

APPLICATION IN AIRPLANE DESIGN

Beginning first with the original conception of the design, it is usually the case that the design requirements are very definite; *i.e.*, there is a specification to meet. This specification, in most cases, has been written by a group of engineers who have a thorough knowledge of their organization's requirements. For a commercial airplane, a certain route of so many miles must be covered in a specified time under a specified load. Rigid soundproofing, vibration, and passenger-comfort requirements must be considered also in the initial mapping out of the design, in order

that a rough picture of the whole design may be had before establishing even the wing area.

If the airplane is for military use, the specification will probably require a high speed of so many m.p.h., a given bomb-load capacity, a range of so many miles, and certain take-off, landing, and other requirements.

Wings.—First approximations of the gross weight are made by experience or by comparison with other designs. A wing loading is selected consistent with proposed flap design and desired landing and take-off requirements. Assume that a gross weight of 36,000 lb. will be adequate and that a stalling speed of 70 m.p.h. at sea level with flaps down must be met. The maximum lift coefficient obtained with a flapped wing varies greatly depending on the type of flap used. A reasonable value, typical of many modern designs, is approximately $C_{L\,\max} = 2.2$.

Therefore the wing area may be calculated from the equation

$$\text{Lift} = \text{weight} = C_L S \tfrac{1}{2}\rho V^2$$

where weight = 36,000 lb.

$C_{L\,\max} = 2.2.$

$\rho = 0.002378$ slugs/cu. ft. at sea level from N.A.C.A. standard atmosphere.

$V = 70 \text{ m.p.h.} = 70 \times \frac{88}{60} = 103 \text{ ft./sec.}$

$$S = \frac{36{,}000}{2.2 \times \frac{1}{2} \times 0.002378 \times 103^2} = 1{,}300 \text{ sq. ft.}$$

The choice of the airfoil section for the wing is not so wide as might be expected. Actually the N.A.C.A. 230 series airfoil has been used extensively on modern designs varying from multi-engine bombers to gliders. This airfoil has low drag and high lift characteristics and appears optimum for all-round performance for almost any type of airplane.

The choice of a wing plan form and thickness is governed in general by the range requirements. The thickness at the root, or center line, of the wing is usually about 4 to 6 per cent of the wing semispan, with the thickness tapering to a section about 10 per cent thick at the tip. The plan form must provide the 1,300 sq. ft. of wing area required, with a span selected as follows:

It is apparent that, the lower the drag, the higher the performance and the less fuel required for a specified range. Referring to the basic force equations we again note that the drag is

composed of two parts, parasite and induced. The parasite drag is controlled by refinement of design and the elimination of protuberances, which will be achieved to an extent consistent with the weight penalty and manufacturing complications involved. The induced drag, however,

$$D_i = \frac{L^2}{\pi b^2 \frac{1}{2}\rho V^2}$$

is dependent solely on the one physical characteristic, span, and varies inversely as the square of this dimension. Therefore, increasing the span by 10 per cent will reduce the induced drag by approximately 20 per cent. It appears, therefore, that the span should be very large for greatest efficiency of design. Large span, however, increases the wing weight since the gross weight is supported at a greater arm and the bending moment in the wing is greater. A compromise is therefore made, consistent with the previous experience of the manufacturer with respect to building high aspect-ratio wings and the weight involved.

Fuselage.—The fuselage, or hull, is next selected depending on whether the design is a landplane or flying boat. Other types of airplane are amphibians and seaplanes with floats attached, usually to a landplane type of fuselage. Fuselages are relatively simple to design as compared with flying-boat hulls, since there are only the interior capacity and aerodynamic qualities to consider. The fuselage is therefore given the smallest streamline form consistent with the interior capacity and arrangement of equipment required. In military designs where a certain bomb capacity, various gun-turret locations, numerous items of equipment, and a high degree of visibility are required, little choice of fuselage shape is left to the designer after an adequate tail length is provided for good stability and control without excessively large tail surfaces. Usually the fuselage drag is a necessary evil that cannot be obviated except to the extent of providing a clean design without protuberances or discontinuities. Flying-boat hulls require additional consideration with respect to the design of the bottom for good hydrodynamic characteristics of low water resistance, good spray pattern, and lack of "porpoising" tendencies.

Tail.—The tail surfaces usually are one of two types, single vertical tail or twin vertical tail. Both have their respective

merits, and the choice of type usually is dictated by other than aerodynamic considerations. Tail-surface areas are roughly about 25 to 35 per cent of the wing area for airplanes with high lift flaps. Actual selection of tail size and form deserves much study and a thorough analysis of the control and stability requirements of the particular design. Control surfaces are normally about 35 to 45 per cent of the total surface chord and have 20 to 30 per cent aerodynamic balance. Aerodynamic balance is defined as the percentage of surface area forward of the hinge line.

Before the universal use of trim tabs, the stabilizer was adjustable to give the tail the angle of attack required to trim the airplane to the desired attitude. This was a very unsatisfactory method; for, in large airplanes, severe problems were encountered in moving the large surface involved.

The trim tab is small and fairly simple to add to the tail surfaces. It is used on the elevator to obtain the longitudinal trim desired and on the rudder to provide directional trim as in the case of flight with part of the engines inoperative. Trim tabs on the ailerons provide lateral trim as in the case of off-center loading and wing heaviness. Aileron tabs are also used in conjunction with rudder tabs in trimming for flight with part of the engines inoperative.

Nacelles.—Engine nacelles are made as small as the selected engine installation will allow. The well-known Pratt and Whitney R-1830 double-row 1,200-b.hp. engine is 48 in. in diameter; and if the oil cooler and carburetor air scoops are hung outside, the engine can be cowled in by a nacelle only 49 in. in diameter. Even the largest of radial engines, developing over 2,000 b.hp., is little greater in diameter. If the oil cooler, carburetor air scoop, and intercoolers, in the case of two-stage and turbo installations, are all included within the nacelle contour, the nacelle must necessarily be increased in size somewhat over the diameter of the engine.

Performance.—Next the design is considered from the performance angle to see if the selected component parts add up to the desired result. For rough approximations a simple rule-of-thumb method may be used in the drag estimate.

Drag.—Wing and tail drags are approximately $C_{D_P} = 0.01$, based on the plan form of the surface. All other items have a

drag of approximately $C_{D_f} = 0.10$, based on the frontal area. In evaluating the drag characteristics, it is convenient to use the equivalent parasite area which is defined as $f = C_{D_p}S$ and is merely the equivalent area of drag coefficient = 1.0, which will give the same drag as the component part it represents. Therefore we have

$$\text{Wing drag, } C_{D_p} = 0.01$$
$$\text{Wing area} = 1{,}300 \text{ sq. ft.}$$
$$f = 1{,}300 \times 0.01 = 13.0$$

Tail drag, $C_{D_p} = 0.01$

Horizontal and vertical tail area = approximately $0.30 \times 1{,}300$ = 390 sq. ft.

Tail drag = $f = 390 \times 0.01 = 3.90$

Assume the fuselage is 8 ft. in diameter.

$$\text{Frontal area} = \frac{8^2\pi}{4} = 50 \text{ sq. ft.}$$
$$\text{Fuselage drag, } C_{D_f} = 0.10$$
$$f = 50 \times 0.10 = 5.0$$

Assume the design has four engines of 48 in. diameter.

Total frontal area for 49-in.-diameter nacelles

$$= \left(\frac{49}{12}\right)^2 \left(\frac{\pi}{4}\right) \times 4 = 52.5 \text{ sq. ft.}$$

Nacelle drag, $C_{D_f} = 0.10$

$f = 52.5 \times 0.10 = 5.25$

Miscellaneous protuberances, etc., estimated as $f = 1.5$.

The total equivalent parasite area, therefore, is 28.65 and

$$C_{D_p} = \frac{28.65}{1{,}300} = 0.0220$$

The drag is therefore

$$C_D = C_{D_p} + C_{D_i}$$
$$= 0.0220 + \frac{C_L^2}{\pi R}$$

except that the loading on the wing is never ideal and the minimum induced drag is not realized. Actually the induced drag arises from an effective aspect ratio or effective span, which is always smaller than the actual span.

$$\left(\frac{b_e}{b}\right)^2$$

where b_e = effective span.
b = actual span.
e = span efficiency.

If we select an aspect ratio of 10 for the subject design, the span efficiency will be approximately 0.85 and the final drag equation is

$$C_D = 0.0220 + \frac{}{10\pi \times 0.85} = 0.0220 + 0.038C_L^2$$

When the design has been substantially settled, a wind-tunnel model is usually built and tested to check the original drag estimates.

Speed.—Sufficient data are now available to estimate the high speed. The power plants selected are assumed to be supercharged and to deliver 1,200 b.hp. at 10,000 ft. Assuming a propeller efficiency of 0.85, the total thrust horsepower available

$$\text{T.H.P.}_A = 4 \times 1{,}200 \times 0.85 = 4{,}070$$

Assume that

$$\begin{aligned}\text{High speed} &= 300 \text{ m.p.h. at } 10{,}000 \text{ ft.}\\ &= 440 \text{ ft./sec.}\end{aligned}$$

$$C_L = \frac{W}{S\frac{1}{2}\rho V^2} = \frac{36{,}000}{1{,}300 \times \frac{1}{2} \times 0.002378 \times 0.7384 \times 440^2} = 0.163$$

where ρ = 0.002378 at sea level and 0.7384 is the ratio of the density at 10,000 ft. to the density at sea level from N.A.C.A. standard atmospheric tables. That is,

$$\sigma = \frac{\rho_{10,000}}{\rho_0} = 0.7384$$

$$C_D = 0.0220 + \frac{0.163^2}{10\pi \times 0.85} = 0.0220 + 0.0010 = 0.0230$$

$$\text{Drag} = C_D S \tfrac{1}{2} \rho V^2 = 0.0230 \times 1{,}300 \times \tfrac{1}{2} \times 0.002378 \times 0.7384 \times 440^2$$
$$= 5{,}090 \text{ lb.}$$

The thrust horsepower required

$$\text{T.H.P.}_R = \frac{DV}{550} = \frac{5{,}090 \times 440}{550} = 4{,}070$$

Therefore the high speed is 300 m.p.h. at 10,000 ft. since the thrust horsepower required and thrust horsepower available are equal at this speed. Of course, in an actual performance analysis, several speeds would be assumed and curves plotted of thrust horsepower required and thrust horsepower available vs. air speed to obtain an intersection of the thrust horsepower required and thrust horsepower available curves at the high speed.

Range.—In order to compute the range of the airplane a further development, using the original basic force equations, is required. It is evident that the endurance, or time of flight, is

$$E \text{ (hours)} = \frac{\text{fuel (pounds)}}{\text{lb./hr. of fuel consumed}}$$

The range, then, is

$$R \text{ (miles)} = EV$$

where V is in m.p.h., or

$$R = \frac{VF}{\text{lb./hr.}}$$

where F = fuel in pounds.

The fuel consumed in pounds per hour is entirely a power-plant characteristic and depends for the major part only on the r.p.m. and brake horsepower being delivered. It is convenient therefore to designate the fuel flow in pounds per brake horsepower per hour or as specific fuel consumption

$$\text{s.f.c.} = c = \frac{\text{lb./hr.}}{\text{b.hp.}}$$

The thrust horsepower delivered by the propeller is $\eta \times$ brake horsepower where η is the propeller efficiency. The expression

for range, therefore, may be written

$$R = \frac{VF}{c(\text{T.H.P.}/\eta)} \qquad \text{or} \qquad R = \frac{VF(\eta/c)}{\text{T.H.P.}}$$

in which

$$\text{T.H.P.} = \text{T.H.P.}_R \text{ for level flight} = \frac{DV}{550} = \left(C_D S \frac{1}{2} \rho V^2\right) \frac{V}{550}$$

and

$$R \text{ (miles)} = \frac{F(\eta/c)550 \times \frac{60}{88}}{C_D S \frac{1}{2} V^2}$$

Substituting $V^2 = W/C_L S \frac{1}{2} \rho$ gives

$$R = \frac{F(\eta/c)550 \times \frac{60}{88} C_L S \frac{1}{2} \rho}{C_D S \frac{1}{2} \rho W}$$

Also,

$$\frac{C_L}{C_D} = \frac{L}{D} \qquad \text{and} \qquad R = F\,(\eta \quad 375 \left(\frac{L}{D}\right)\left(\frac{1}{W}\right)$$

If the fuel F is taken as dw and the expression is integrated from W_0 to W_1 where W_0 is the initial gross weight and W_1 is the final gross weight $(W_0 - F)$,

$$\begin{aligned} R &= 375 \left(\frac{\eta}{c}\right)\left(\frac{L}{D}\right) \int_{W_0}^{W_1} \frac{dW}{W} \\ &= 375 \left(\frac{\eta}{c}\right)\left(\frac{L}{D}\right) (\log_e W_0 - \log_e W_1) \\ &= 375 \left(\frac{\eta}{c}\right)\left(\frac{L}{D}\right) \log_e \left(\frac{W_0}{W_1}\right) \\ &= 863.5 \left(\frac{\eta}{c}\right)\left(\frac{L}{D}\right) \log_{10} \left(\frac{W_0}{W_1}\right) \end{aligned}$$

which is the familiar Bréguet range equation. It is apparent that the maximum range will occur at the maximum L/D ratio. $(L/D)_{\max}$ may be determined as follows:

$$\begin{aligned} C_D &= C_{D_P} + C_{D_i} \\ \frac{L}{D} &= \frac{C_L}{C_D} = \frac{C_L}{C_{D_P} + C_{D_i}} \\ C_{D_i} &= \frac{C_L}{\pi Re} \qquad \text{and} \qquad f = \frac{C_{D_P}}{S} \end{aligned}$$

and

$$D \quad (f/s) + (C_L^2/\pi Re)$$

$$\frac{L}{D} = \frac{C_L \pi ReS}{\pi Ref + SC_L^2}$$

Differentiating this with respect to C_L, equating to zero, and solving for the C_L which gives the maximum value of L/D,

$$\frac{d(L/D)}{dC_L} = 0 = \frac{(\pi Ref + SC_L^2)\pi ReS - C_L \pi ReS \times 2SC_L}{(\pi Ref + SC_L^2)^2}$$

$$\pi Ref \pi ReS + SC_L^2 \pi ReS - 2SC_L^2 \mu ReS = 0$$

$$\pi^2 R^2 e^2 Sf = \pi ReS^2 C_L^2$$

$$C_L \text{ for } \left(\frac{L}{D}\right)_{\max} = \sqrt{\frac{f}{S}\pi Re}$$

The other root of the equation is imaginary.

$$\left(\frac{L}{D}\right)_{\max} = \frac{C_L}{(f/S) + (C_L^2/\pi Re)}$$

$$= \frac{\sqrt{(f/S)\pi Re}}{\dfrac{f}{S} + \dfrac{f/S\pi Re}{\pi Re}} = \frac{\sqrt{(f/S)\pi Re}}{2(f/S)}$$

$$= \frac{1}{2}\sqrt{\frac{\pi Re}{f/S}} = \frac{1}{2}\sqrt{\frac{\pi Re}{C_{D_P}}}$$

or

$$\left(\frac{L}{D}\right)_{\max} = \frac{1}{2}\sqrt{\frac{\pi b^2 e}{f}}$$

Therefore, $(L/D)_{\max}$ for the airplane under consideration is

$$\left(\frac{L}{D}\right)_{\max} = \frac{1}{2}\left(\frac{\pi \times 10 \times 0.85}{0.0220}\right)^{\frac{1}{2}} = 17.4$$

and if the fuel is assumed to be 1,000 gal., the maximum range will be

$$R_m = 863.5 \times 1.7 \times 17.4 \log_{10}\left(\frac{36{,}000}{36{,}000 - 6 \times 1{,}000}\right)$$
$$= 2{,}050 \text{ miles}$$

(NOTE: Fuel weighs 6 lb. per gal.)

The above value of η/c of 1.7 is based on a propeller efficiency of 0.80 and an s.f.c. of 0.47 which is representative of the R-1830 engine at normal cruising powers. The s.f.c. is usually given in the form of the fuel-consumption chart shown in Fig. 8, so that in the range analysis the optimum r.p.m. for cruising may be determined. This is the r.p.m. which will give the maximum value of η/c. In most cases the propeller efficiency decreases as the r.p.m. is lowered; but, from the fuel-consumption chart, we see that the s.f.c. is also reduced by decreasing r.p.m. We

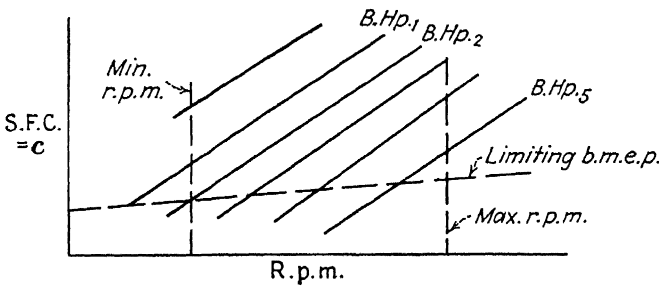


FIG. 8.—Fuel consumption chart.

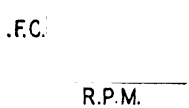


FIG. 9.—Fuel consumption.

FIG. 10.—Propeller efficiency.

therefore have the curves of Figs. 9 and 10, from which it is apparent that η/c plotted against r.p.m. will give the results shown in Fig. 11.

The peak η/c is the only one of interest since it is expected that the optimum r.p.m. will be used in flight. This optimum r.p.m. can be determined only by flight testing or by estimation by calculation. Certain limitations in operating the engines exist and must be recognized in making the range calculations. First there is a top limit on brake horsepower and r.p.m. for continuous cruising. The maximum brake mean effective pressure (b.m.e.p.) is also specified. Practically, there is a minimum r.p.m. at which the engine will function satisfactorily. Therefore, we see that the only unrestricted portion of the s.f.c.

chart is upward where it is undesirable to cruise if maximum η/c is desired.

There is an additional limitation that is inherent and cannot be modified for a particular engine. Engine power curves are usually given in the form shown in Fig. 12. For any selected altitude for cruising there is a maximum brake horsepower that the engine will deliver for each r.p.m. These values may be plotted on the previous s.f.c. chart to give a critical altitude limit.

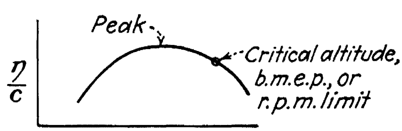


FIG. 11.—Parameter η/c vs. r.p.m.

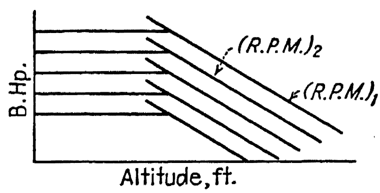


FIG. 12.—Engine power-altitude curve.

Therefore the maximum η/c may not be attainable at the higher altitudes since the critical altitude, or the supercharging limit of the engine, may be reached, where it is impossible to reduce the r.p.m. further and maintain the brake horsepower required.

In the case of two-speed and two-stage engines, where there are two and three degrees of supercharging, respectively, each condition of cruising must be analyzed for each amount of supercharging. It may be found that the highest η/c is obtained by using the higher supercharger speed or second stage of supercharging, it being thus possible to use lower r.p.m. and higher b.m.e.p. For mechanical supercharging, the engine power diverted to the supercharger blower is lost to the propeller, and fuel is required to furnish this power. Therefore the s.f.c. will be higher, based on the brake horsepower when using higher degrees of supercharging.

Climb and ceiling calculations involve calculation of the thrust horsepower required and thrust horsepower available for various speeds and altitudes. A plot of these data is shown in Fig. 13.

The maximum rate of climb in feet per minute is

$$\frac{(\text{Maximum excess horsepower}) \times 33{,}000}{W}$$

Plotting the rate of climb vs. altitude will give the results shown in Fig. 14.

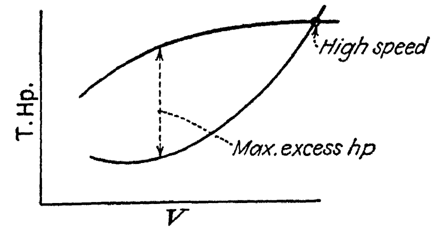


FIG. 13.—Thrust horsepower available.

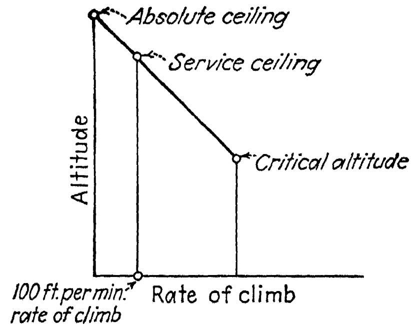


FIG. 14.—Rate of climb.

Take-off and Landing.—Take-off and landing are analyzed as follows: Applying Newton's law, $F = Ma$, where F = force, M = mass of airplane, and a = acceleration or deceleration, gives

$$\text{Force} = \text{accelerating or decelerating force} = \left(\frac{W}{g}\right) a$$

where the accelerating force is the excess thrust for take-off and the decelerating force is the frictional and aerodynamic drag on landing and W is the weight of the airplane and g is the acceleration due to gravity.

The thrust can usually be expressed accurately by

$$= T_0 - \left(\frac{dT}{dV^2}\right) V^2$$

where T_0 is the static thrust at $V = 0$ and dT/dV^2 is the variation of the thrust with V^2 which is the velocity squared.

Also,

$$\frac{dv}{dt} = a \tag{10}$$

where t is the time
and

$$\frac{ds}{dt} = v \tag{11}$$

where s is the distance.
Therefore, dividing Eq. (11) by Eq. (10) gives

$$\frac{ds}{dv} = \frac{v}{a}$$

from which

$$\int ds = \int \left(\frac{V}{a}\right) dv$$

Integrating,

$$s = \int_0^{V_T} \left(\frac{v}{a}\right) dv$$

where V_T = take-off velocity.

The acceleration must first be evaluated in terms of V before the integration can be performed. We have

$$F = Ma = \left(\frac{W}{g}\right) a$$

For take-off, there is the thrust T, the aerodynamic drag D, and the ground frictional drag R. Therefore, the accelerating force is

$$\begin{aligned} T_e &= T - D - R \\ D &= C_D S \tfrac{1}{2} \rho V^2 \\ R &= \mu(W - L) = \mu(W - C_L S \tfrac{1}{2} \rho V^2) \end{aligned}$$

where μ is the coefficient of ground friction and has values ranging from 0.02 to about 0.10 for various types of runways. Therefore, we have

$$\begin{aligned} T_e &= T_0 - \left(\frac{dT}{dV^2}\right) V^2 - C_D S \frac{1}{2} \rho V^2 - \mu \left(W - C_L S \frac{1}{2} \rho V^2\right) \\ &= V^2 \left(C_L S \frac{1}{2} \rho \mu - C_D S \frac{1}{2} \rho - \frac{dT}{dV^2}\right) + (T_0 - \mu W) \end{aligned}$$

From the foregoing,

$$T_e = \frac{W}{g} a, \qquad a = \frac{gT_e}{W}$$

Substituting gives

$$S = \int_0^{V_T} \frac{(W/g)V\,dV}{V^2\,[S\tfrac{1}{2}\rho(\mu C_L - C_D) - (dT/dV^2)] + (T_0 - \mu W)}$$

Integrating and substituting $V_T{}^2 = W/\frac{1}{2}\rho S C_{L_T}$ gives

$$S = \frac{W}{2g[\frac{1}{2}\rho S(\mu C_L - C_D) - (dT/dV^2)]} \log_e \left\{ \frac{[\frac{1}{2}\rho S(\mu C_L - C_D) - (dT/dV^2)]W}{(T_0 - \mu W)(\frac{1}{2}\rho S C_{L_T})} + 1 \right.$$

where C_L and C_D correspond to the average take-off attitude and C_{L_T} is the take-off C_L. In the case of a tricycle gear, the attitude is substantially constant until just at take-off where the angle of attack is quickly increased to C_{L_T}.

Similarly, for landing we have

$$S = \frac{(W/S)}{\rho g(C_D - \mu C_L)} \log_e \left[\frac{C_D + \mu(C_{L_M} - C_L)}{\mu C_{L_M}} \right]$$

where the development is identical to that for take-off except that the expression for thrust is not present and the coefficient of ground friction is between 0.20 and 0.60 depending on the degree of braking available.

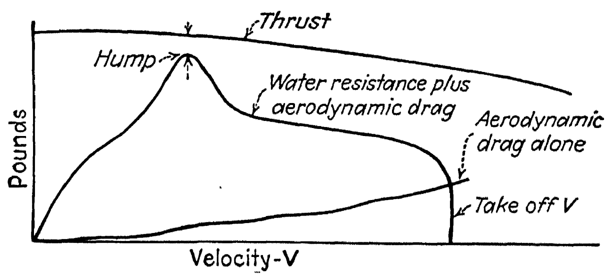


FIG. 15.—Take-off resistance of a flying boat.

For take-off of flying boats the analysis is somewhat more complicated since the variation of the water resistance with speed cannot be expressed mathematically. The resistance is usually

calculated for a series of speeds and the integration done graphically. The variation of the water and aerodynamic drag or resistance with speed is usually of the form shown in Fig. 15.

If the hump resistance exceeds the thrust, the airplane will not take off. In the case of a landplane the resistance appears as in Fig. 16, so that the take-off, in general, is primarily a matter of adequate runway length.

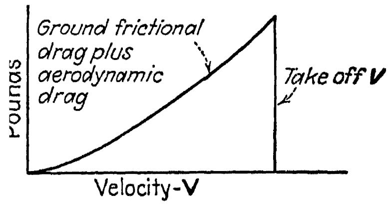


FIG. 16.—Take-off resistance of a landplane.

Balance.—The design must now be checked for balance. That is, the longitudinal moments produced by the various items of equipment and component parts of the airplane must be summed up to find the resultant center of gravity (c.g.). Good flying qualities and efficiency of design dictate that the c.g. must be near the c.p. of the wing or slightly back of the c.p. This usually means the selection of the fore-and-aft position of the wing relative to the fuselage, or hull. It usually determines the sweepback of the wing, also.

Wing incidence is normally selected to give the fuselage a minimum drag attitude when the wing is at the angle of attack required at high speed to lift the weight of the airplane. The stabilizer is set at an angle to the wing so that the airplane is in aerodynamic trim at high speed with the elevator at zero. The elevator trim tab, which in turn deflects the elevator, is used to trim at other speeds.

So far no consideration has been given to the design of wing flaps except that a maximum lift coefficient of 2.2 was assumed. Normally, ailerons of approximately 40 per cent span are required, which leaves 60 per cent span for flaps.

Wing flaps may be of various forms, plain, split, slotted, or Fowler, the maximum lift and drag varying widely. It is usually true that the highest lift flap weighs the most and is most expensive to build, so that the choice of flap type must be considered from all viewpoints.

Wind-tunnel Tests.—After the design has progressed to a point where the wing plan form, fuselage size, etc., are fairly definite, a wind-tunnel model is built. The size of the model depends entirely on the wind tunnel available for the test, the

model being made as large as possible. Span is usually the critical dimension and is made the same as the tunnel diameter, or width, less 12 to 24 in. for clearance between the tunnel wall and wing tips. The accuracy of construction varies from 0.002 to 0.01 in. depending on the purpose of the test and the material used. Most models are made of laminated mahogany or birch and are given a finish with a high polish. The finish of a model surface is very important since varying degrees of roughness cause varying degrees of skin friction. It is rather difficult consistently to evaluate the degree of roughness especially if it is not uniform over the entire model. Roughness will produce greater effects on certain parts of the model than on other parts. For instance, roughness on the wing leading edge or cowl leading edge or on any forward part of a body will no doubt produce more drag than the same degree of roughness located well back on the wing or fuselage. It has been found that a model will collect dust and dirt, when tested for several hours, to the extent that the drag will increase appreciably even though the model appears clean to the eye. Consequently, during drag tests, models are usually polished with a soft cloth after each run. Great care is also exercised to keep the tunnel swept out and free from dirt, particles of wax, etc., that may be carried into or dropped in the tunnel unintentionally. Needless to say, it is usually disastrous to the model or wind-tunnel propeller to leave small tools, etc., in the tunnel.

Tunnel speeds range from 100 to 200 m.p.h. for most normal test work. High-speed tunnels attain speeds over 500 m.p.h.; however, speeds of this magnitude are rarely used for routine tests. In any event, one must have had considerable experience in a tunnel before being able to evaluate data properly. This is especially true of drag data. In most cases, empirical corrections are made to wind-tunnel drag data for conversion to full scale, rather than using doubtful extrapolations with the Reynolds number and then adding corrections due to roughness, etc. After several designs have been tested in a specific tunnel and these data correlated with flight tests, a fairly reliable basis can be established for prediction of full-scale characteristics from other model tests.

Models are suspended either by wires or by struts. In the very high-speed tunnels the model may be mounted at the wing tips,

the wing in this case extending completely through the tunnel wall. Open-throat tunnels offer many advantages over the closed-throat tunnels in respect to accessibility and means of mounting models. The open throat is almost a necessity for tunnels such as the N.A.C.A. full-scale tunnel in which very large models or full-scale airplanes are tested.

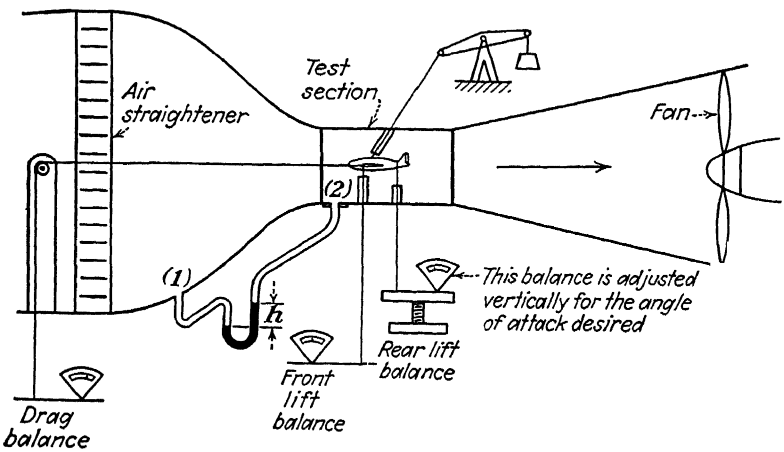


FIG. 17.—Diagram of a typical wind tunnel.

The wind tunnel in its simplest form is shown diagrammatically in Fig. 17. The air is always drawn through the test section and never blown. It is obvious that the air flow in the test section must be uniform in velocity, direction, and turbulence over the entire test section. Otherwise, the model will not register the forces produced in a uniform air stream such as is obtained in full scale. The wire suspension shown is the three-component type and measures lift, drag, and pitching moment. By using more wires and rearranging the suspension, the other three components, yawing moment, rolling moment, and side force, can be measured also.

Suspension wires and struts are always shielded by streamline tubing in order to reduce the tare drag of the wires.

In the system shown, drag is registered by the forward balance, lift is obtained by summation of the two lift-balance readings, and pitching moment is calculated from the rear lift-balance reading and the corresponding moment about the front attachment point

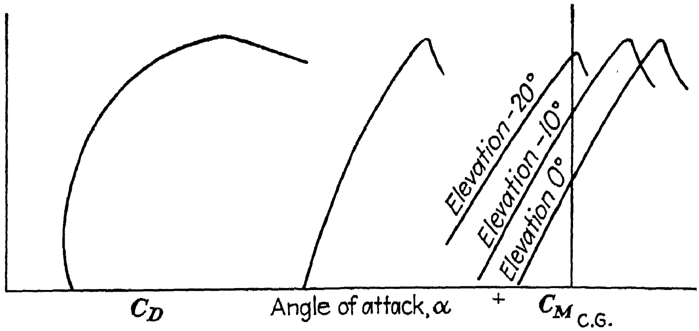


FIG. 18.—Polar and angular representation of coefficients.

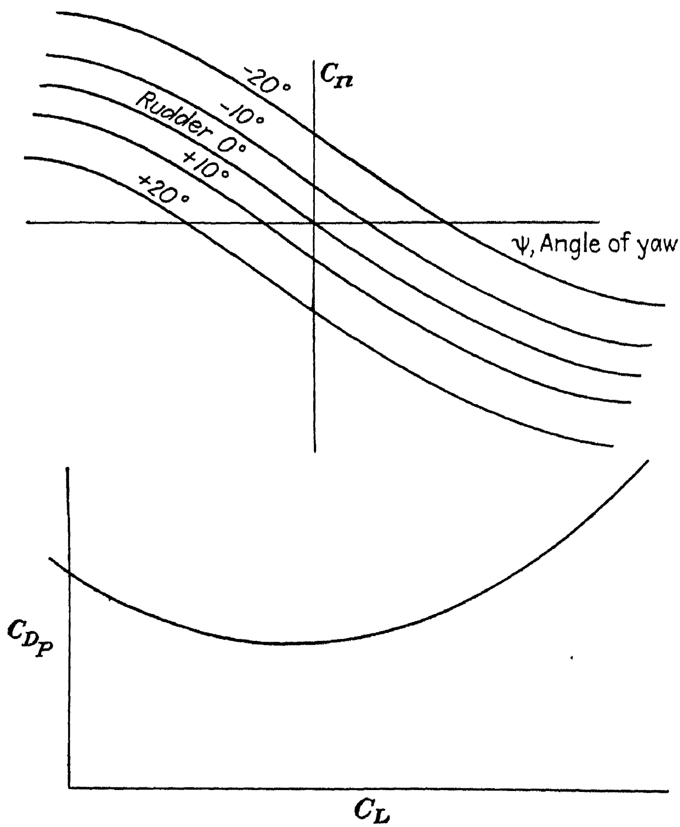


FIG. 19.—Representation of coefficients as obtained in wind tunnel.

on the model. The observed moment can then be transferred to the c.g.

No attempt is made to simulate the weight or weight distribution of the full-scale airplane since the model is rigidly suspended and the forces arising from the dead weight of the model are absorbed by the tension in the rigging. Considerable tension is produced in the rigging by addition of weights to the supporting beam. The static forces of the rigging are read with the tunnel speed at zero. Any change in balance reading with an air flow in the tunnel is therefore due to aerodynamic forces.

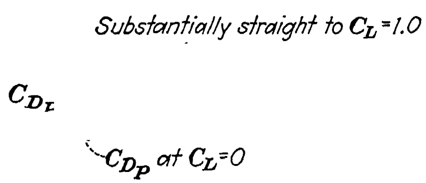


FIG. 20.—Plot for determination of equivalent parasite area.

The speed of the tunnel is measured in the same manner as previously indicated for flow in a tube of varying cross section. Placing static-pressure connections at points (1) and (2) (Fig. 17) and connecting these to a U tube as shown will give the differential pressure between the two points. This pressure differential indicates the velocity as previously described.

The observed data from wind-tunnel tests are in pounds and are converted to the coefficient form for study and application. Typical plots are shown in Figs. 18 and 19. All these coefficients are the same as previously discussed, with one exception. Since the span efficiency e is an experimental value, it is not used in the calculation of the induced drag and C_{D_P}. C_{D_P}, in this case, is

$$C_{D_P} = C_D - \frac{C_L^2}{\pi R}$$

The equivalent parasite area f and the span efficiency e are determined as follows: Replotting the C_{D_P} vs. C_L data as C_{D_P} vs. C_L^2 gives the result shown in Fig. 20. Therefore, C_D may be written

$$C_D = C_{D_P}\ (\text{at } C_L = 0) + \left(\frac{dC_{D_P}}{dC_L{}^2}\right) C_L{}^2 + \frac{C_L{}^2}{\pi R}$$

$$f = C_{D_P}\ (\text{at } C_L = 0) \times S$$

$$\frac{C_L{}^2}{\pi Re} = \left(\frac{dC_{D_P}}{dC_L{}^2}\right) C_L{}^2 + \frac{C_L{}^2}{\pi R}$$

$$= C_L{}^2 \left[\left(\frac{dC_{D_P}}{dC_L{}^2}\right) + \frac{1}{\pi R}\right]$$

$$e = \frac{1}{\pi R(dC_{D_P}/dC_L{}^2) + 1}$$

The span efficiency e could also be determined from a plot of C_D vs. $C_L{}^2$ where

$$e = \frac{1}{\pi R(dC_D/dC_L{}^2)}$$

The slope dCm/dC_L is representative of the static longitudinal stability. It may vary from -0.10 to -0.20, depending on the type of airplane. For range four-engine airplanes, dCm/dC_L is usually -0.17 to -0.19 for satisfactory longitudinal stability.

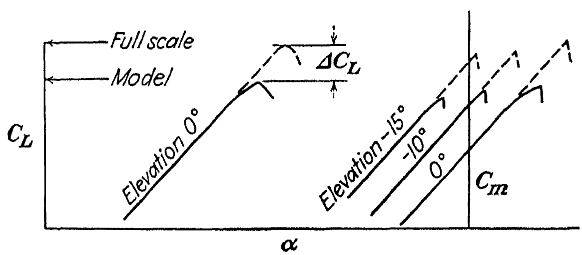


FIG. 21.—Extrapolation to full-scale values from model tests.

The slope $dCn/d\psi$ is representative of the static directional stability. Values of -0.0006 to -0.0012 are obtained, with about -0.0010 applying to large four-engine types. Cross plots of the elevator and rudder moment curves give dCm/de and dCn/dr which are indicative of the elevator and rudder effectiveness, respectively; *i.e.*, these slopes indicate the amount of moment produced by 1 deg. of surface deflection. These values are about -0.0020 and -0.0010, respectively.

When the C_m vs. C_L curves are obtained with flaps deflected, an indication of the elevator control is obtained. If the airplane can be trimmed in the air at $C_{L\,\max}$ full scale, with flaps down

and 15 to 20 deg. of elevator, it should be satisfactory (see Fig. 21). Model lift data are first extrapolated to the full-scale Reynolds number for this determination.

The increment ΔC_L is approximately 0.4 for extrapolation from R.N. $= 1.0 \times 10^6$ to 8.0×10^6 or above. If 15 deg. of elevator will trim at the full-scale C_{Lm}, as shown, the elevator control on the full-scale airplane should be satisfactory.

Rudder control is obtained in a similar manner. Cross plotting the yawing-moment data for $C_n = 0$ gives the angle of yaw that can be held with the rudder (see Fig. 22). At least 18 deg. of yaw should be held by maximum rudder.

Power Tests.—So far the discussion has been limited to testing without model propellers. Much valuable data are also obtained by repeating all the above tests with running propellers. Small

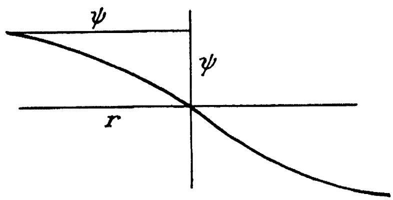


FIG. 22.—Yawing moment plotted from model tests.

electric motors developing from 5 to 40 b.hp. are used, depending on the size of the model. A motor 4 in. in diameter by 6 in. long will develop about 15 b.hp. It often occurs, therefore, that a small wind-tunnel model of around 8 or 9 ft. span will develop more power than is used by some of the present-day light airplanes.

Power tests are run principally to determine the destabilizing effect of power on stability. Very often these tests indicate that drastic changes are necessary in the design in order to get satisfactory stability with power on. The effect of oppositely rotating propellers, also, can be checked; and rudder control with engines inoperative may be determined.

Very accurate model propellers are built for these tests. Propeller hubs are less accurate in shape, the primary requirement here being alignment, since propeller speeds range from 12,000 to 18,000 r.p.m. These speed and power conditions demand precision construction of the motors, also. Bearings are the

greatest problem; for, even with water cooling, it is difficult to keep the temperature down when the motor is run at high power for long periods. Cooling water temperatures run around 130 to 150°F.

Tail sizes for the required static longitudinal and directional stability can be computed with fair accuracy for power off; however, computation of the effect of power on stability is as yet unreliable, and testing is used entirely for determination of this effect.

After completion of the preliminary design, the project is usually broken down and distributed to the various groups for detail design of the wing, fuselage, power-plant installation, etc. However, close contact is maintained among all groups on all aerodynamic problems as the design progresses. Often, additional wind-tunnel tests are needed. Tests may be made later of isolated parts of the airplane, such as a large-sized engine nacelle, for the design of propeller spinners, engine ducts, etc.

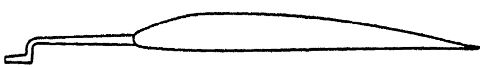


FIG. 23.—Air-speed head mounted on wing leading edge.

Flight Testing.—The flight testing of the completed airplane is the final job before the airplane is delivered. Here the flight-test personnel under the direction of the chief flight-test pilot test the airplane for stability and control, engine operation and cooling, operation and functioning of all equipment, performance, and ability to meet guarantees. Engineering flight-test observers are members of the aerodynamics group and, in general, take all data during the flight testing. These data are worked up and reports of the flights written by these observers.

Air-speed Indicator.—In the performance testing of an airplane, the first item, after the shakedown flights, is the calibration of the air-speed indicators. These instruments have a negligible mechanical error; but, owing to the proximity of the air-speed head to the airplane, there is usually a position error of about 5 to 7 m.p.h., depending on the location. Quite often the head is installed on the wing, as shown in Fig. 23. This location is, in general, a poor one, for it gives rather large position errors. A location that is more favorable is just above the pilot's enclosure

where, if the airplane nose is not long, the error will be of acceptable magnitude.

The position error is due largely to an error in the static pressure. The total head reading is practically unaffected by angularities of flow up to 10 or 15 deg. Sometimes air-speed heads are artifically made to read correctly by placing a small ring ahead of the static openings, as shown in Fig. 24. This produces a low-pressure area just back of the ring; and, by proper adjustment fore and aft, static-pressure errors can be compensated, for the error arises largely from angularity of flow, causing dynamic pressure to be registered in the amount of the vectorial component of the flow.

The air-speed calibration is usually obtained by timed runs over a speed course of known length. The course is usually 4 to 6 miles in length, and runs are made in both directions to cancel wind effects. For example, a 5-mile speed course is used, and the time required to run the course is 80 sec. north and 90 sec. south. The ground speeds are $(5 \times 3{,}600)/80 = 225$ m.p.h. and $(5 \times 3{,}600)/90 = 200$ m.p.h. Average ground speed = 212.5 m.p.h. These runs are made as close to the ground as it is safe to do so. For example, the altitude registered on the altimeter is 500 ft., and the outside air temperature is 20°C. The normal altimeter, by virtue of its construction, records pressure changes only. It is always zeroed at N.A.C.A. standard pressure so that the observed altitude is a pressure altitude above a known zero and is rarely the true altitude above the ground. Height above the ground is determined by reference to the pressure altitude existing at the ground.

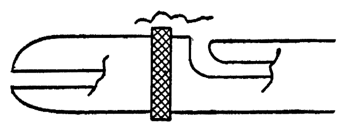


FIG. 24.—Correction ring on an air-speed head.

The air-speed indicator, as previously shown, registers $\frac{1}{2}\rho V^2$, so that the density of the air must be considered. The density of the N.A.C.A. standard atmosphere varies directly as the absolute pressure and inversely as the absolute temperature. Standard conditions are 15°C. and 29.921 in. Hg. Therefore, the altimeter is "zeroed" at 29.921 in. Hg. For example, the density ratio, referred to sea level, is therefore

$$\sigma = \frac{\rho}{\rho_0} = \frac{29.38}{29.921} \times \frac{15 + 273}{20 + 273} = 0.965$$

where the pressure of 29.38 in. Hg is obtained from N.A.C.A. standard atmospheric data for 500 ft. pressure altitude, 15 + 273 is the absolute temperature at standard conditions, and 20 + 273 is the absolute temperature at the operating altitude.

The dynamic pressure is therefore based on the average ground speed which is also the true air speed. Dynamic pressure $= q = \frac{1}{2} \times 0.965 \times 0.002378 \times 212.5^2 \times (\frac{88}{60})^2 = 111.5$ lb. per sq. ft., where 0.002378 is N.A.C.A. standard density at sea level and $\frac{88}{60}$ is the conversion to feet per second. For standard density and a q of 101.5 lb. per sq. ft., the air speed would be

$$= \left[\frac{111.5}{\frac{1}{2} \times 0.002378 \times (\frac{88}{60})^2}\right]^{\frac{1}{2}} = 209 \text{ m.p.h.}$$

If the air-speed indicator were held on 200 m.p.h. for these runs, the error would therefore be −9 m.p.h. at this speed. Plotting the data for several speeds gives the calibration, which is substantially a straight line (see Fig. 25).

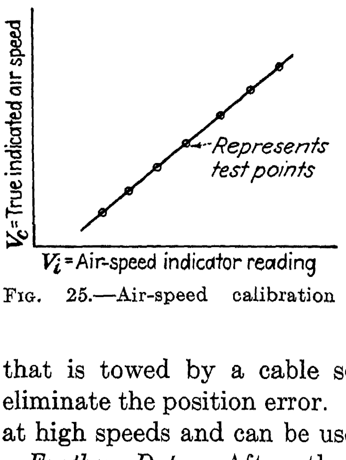


FIG. 25.—Air-speed calibration

The lower end of the calibration curve, in the vicinity of the stall, cannot be run over the speed course because of the danger of flying near the ground at low speeds and is usually obtained with a trailing pilot-static head. This is merely an air-speed head that is towed by a cable some 100 ft. below the airplane to eliminate the position error. Some heads are designed to operate at high speeds and can be used for the complete calibration.

Further Data.—After the air-speed-indicator calibration is complete, all performance data may be obtained. High speed is obtained by flying in stabilized level flight at the desired altitude and recording

1. Air-speed indicator reading.
2. Altimeter reading.
3. Outside-air temperature.
4. Engine r.p.m.
5. Torque-meter reading which indicates the brake horsepower.

Computations are as follows:

Observed data. V_i = 200 m.p.h.
Pressure altitude = 10,000 ft.
Outside-air temperature = −5°C. R.p.m. = 2,500
Torque meter = 170 lb. per sq. in. b.m.e.p.

(NOTE: The torque meter is a device, built into the engine, which registers b.m.e.p. or torque. It is used almost exclusively for all performance testing, for brake horsepower based on the r.p.m. and manifold pressure power calibration are very unreliable.)

Computed data. V_c (true indicated air speed) = 209 m.p.h. from calibration plot, Fig. 25.

$$\frac{\rho}{\rho_o} = \sigma = \frac{20.58}{29.921} \times \frac{273 + 15}{273 - 5} = 0.740$$

$$\tfrac{1}{2} \times 0.002378 \times (\tfrac{88}{60})^2 \times 209^2 = \tfrac{1}{2} \times 0.002378 \times (\tfrac{88}{60})^2 \times 0.740 \times V_t^2$$

$$V_t \text{ (true air speed)} = 209\sqrt{\frac{1}{\sigma}} = 243 \text{ m.p.h.}$$

$$\text{Brake horsepower} = \frac{\text{plan}}{33{,}000}$$

If the engine displacement is 1,830 cu. in. as for the Pratt and Whitney R-1830 engine, then

$$\text{Brake horsepower} = (170 \times 144) \times \left(\frac{1{,}830}{1{,}728}\right) \times \left(\frac{2{,}500}{33{,}000 \times 2}\right) = 985$$

If the rated power is 1,000, the speed can be corrected for small changes in power by $243(1{,}000/985)^{1/3}$ = 245 m.p.h.

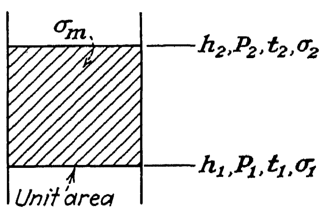


FIG. 26.—Graphic representation of an air column of unit area.

Rate of climb cannot be computed directly from the increments of altimeter reading per unit of time, since the altimeter reads only change in pressure and rate of climb must be based on the actual number of feet climbed in a specified time.

Consider a column of air as shown in Fig. 26. σ_1 and σ_2 are determined, as previously described, from the corresponding temperature t and pressure P

$$\sigma_m = \frac{\sigma_2 - \sigma_1}{2}$$

Then,

$$P_1 - P_2 = (h_2 - h_1) \times 0.002378 \times \sigma$$

$$\Delta h = \frac{P_1 - P_2}{0.002378\sigma_m}$$

$$\text{Rate of climb} = \frac{\Delta h}{\Delta t}$$

where Δt = time interval to climb Δh, which is the actual increment of height.

Best climbing speed, for maximum rate of climb, is determined by climbing at a series of air speeds between two specified altitudes and plotting rate of climb vs. air speed to give a peak rate of climb.

Many other tests are made in flight and on the ground which all go to demonstrate the satisfactory operation of the airplane.

Conclusion.—Thus we have followed the airplane through all the stages from its original conception to its final flight testing. The aerodynamics-group personnel are always in close contact with an experimental design through all these stages, and not until the design goes into production does this group's work cease. Even then aerodynamic problems may arise that were not immediately evident in the experimental article.

For further study in aerodynamic problems and applications, the student is referred to two excellent texts, "Engineering Aerodynamics" by Diehl and "Technical Aerodynamics" by Wood.

The following problems will familiarize the student with some of the simpler details that must be checked in flight testing.

1. A twin-engine airplane is flying level at 15,000 ft. standard pressure altitude ($\sigma = 0.6291$). The gross weight is 25,000 lb., and the wing area is 900 sq. ft., with span 100 ft.

   a. Compute the lift coefficient C_L if the true indicated air speed is 150 m.p.h.

b. Assuming the equivalent parasite area is $f = 25$ sq. ft. and the span efficiency $e = 0.80$, compute the maximum range with 30,000 lb. initial gross weight and 500 gal. fuel. (Assume propeller efficiency $\eta = 0.81$ and s.f.c. $= 0.46$.)

c. Compute the brake horsepower required per engine for (*b*) at the beginning and end of flight, assuming initial gross weight = 30,000 lb. and
final gross weight = 30,000 − 500 × 6 = 27,000 lb.

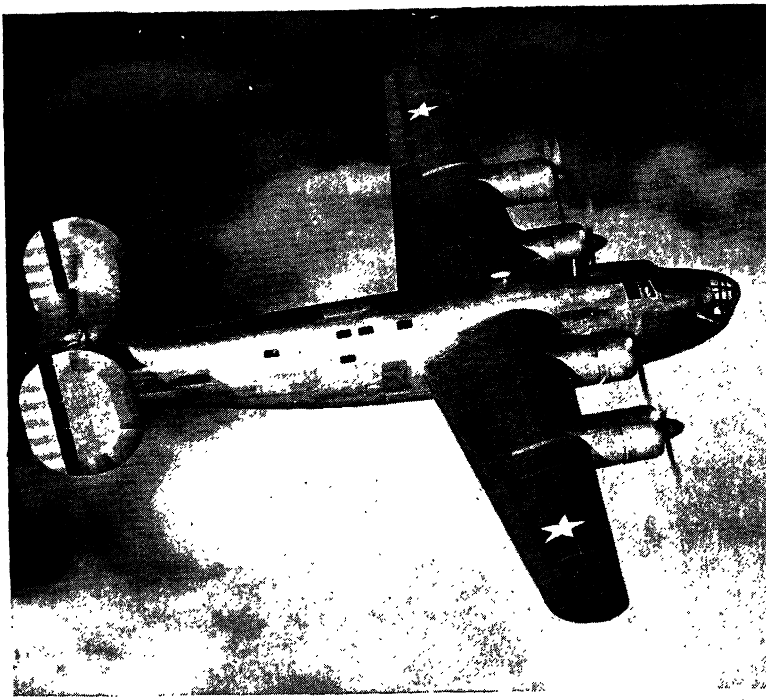
2. A 1:10 scale airplane model is tested in a wind tunnel at 150 m.p.h. in air of standard sea-level density ($\rho = 0.002378$). The observed data are as follows:

Angle of attack α, degrees	Lift, pounds	Drag, pounds	Pitching moment about c.g., foot-pounds	Angle of yaw ψ, degrees	Yawing moment about c.g., foot-pounds
0	51.8	13.15	+15.2	+20	−75.0
+ 2	155.5	14.60	0	15	−64.0
4	259.0	17.60	−15.3	10	−46.6
6	362.5	22.15	−30.1	5	−23.3
8	467.0	28.20	−45.7	0	0
10	570	35.70	−61.0	− 5	+23.2
12	635	41.50	−69.2	−10	46.1
14	640	49.20	−72.9	−15	62.8
				−20	73.1

a. Compute and plot C_L vs. α, C_D vs. C_L, C_{D_P} vs. C_L, $C_{M_{c.g.}}$ vs. C_L, and $C_{N_{c.g.}}$ vs. ψ (neglecting tunnel wall effect) if the full-scale wing area is 900 sq. ft., span 100 ft. and m.a.c. 9.2 ft.

b. Determine the span efficiency e and the equivalent parasite area f.

c. Determine dC_M/dC_L and $dC_N/d\psi$ as representing the static longitudinal and directional stability, respectively.



Consolidated heavy bomber. (*Official photograph, U.S. Army Air Forces.*)

CHAPTER II

POWER-PLANT INSTALLATION

Introduction.—Aircraft power plants have been in production since about 1912 when they took form as internal-combustion engines in the bicycle shop of the Wright brothers. At about the same time Glenn Curtiss developed a four-cylinder, and later a V-8, type of engine which, by the time of the World War, was well known as the OX engine. Previous to this, various attempts at the use of steam for power had been made; but, to date, the excessive weight of boilers and firing equipment has eliminated steam from heavier-than-air use.

In 1914, rotary engines were developed, having from three to nine cylinders extending radially in a plane normal to the crank-

shaft. After the First World War a modification of this type was brought about, making the cylinders stationary and having a revolving crankshaft. Recently, to meet with the need for more power, the cylinders have been arranged in more than one plane so that there now exist twin-row and four-row radial engines.

Usually new engines coming into production are but revisions of the older types in order that more horsepower per pound of engine weight may be developed. Often both the radial and in-line types of engines have been redesigned to accommodate two engines on a single crankcase. In this manner the power output is approximately doubled, and a small number of new parts have to be designed. As a rule this modification does not require any changes in cylinder, piston, connecting-rod, or valve construction so that a great saving in dies, patterns, and tools is achieved.

Radical changes in power plants are the result of years of design, research, and experimentation. They appear only occasionally because of the tremendous cost involved.

Preliminary Design.—The function of the airplane manufacturer's power-plant design group is to design the optimum installation for existing power plants of the required type and power. In the preliminary design group the type and size of engines are determined, and a rough approximation of the location of the engine and nacelle, both of which are given a thorough check in the wind tunnel.

Detail Design.—When the design is given to the detail design groups, the power-plant installation group must determine every last detail of the complete engine and accessory installation and complete the design of the nacelle and attaching parts. Very often a complete mock-up of the installation is made so that minimum clearances may be determined and a space provided for every item of necessary equipment. When the design is finally determined, it is customary to build one complete installation with a nacelle mounted on a dummy wing. The engine is then operated throughout its full speed range, and cooling, torque, and other characteristics are checked. During the operation of this test installation, many changes may become necessary, owing to miscalculations on heat transfer or to mechanical functioning of the accessories and controls.

Power-plant installations may be the result of the airplane manufacturer's effort to develop a new type of airplane or may be developed in answer to a request from a customer for proposals and bids on a new or better airplane. When the experimental airplane is built, all design changes developed on the test stand and from other sources of information have been incorporated. The power plants on the experimental ship are given a run in test and checked thoroughly before the first flight. After acceptance by the customer of the first airplane, production

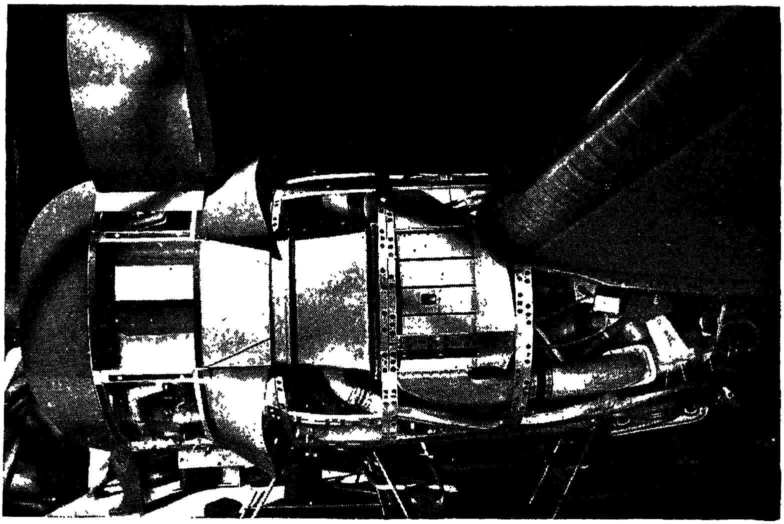


FIG. 1.—Typical engine nacelle, cowl and fairing removed to show air ducts.

drawings for the shop are completed by the power-plant design group. All the work of the group must be done in accordance with the customer's specifications, which vary widely, depending upon the service for which the airplane is destined. A factor considered in the specifications is the range of operating conditions, such as altitude, temperature, and weather.

The large customer organizations and groups have varied opinions as to the type of power plant that is best for a given mission. Thus, no consistent policy or type of design can be recommended to meet any existing condition without first qualifying it to meet the opinion of the customer's trial board.

Types of Engines.—There are two general types of airplane engine, liquid-cooled and air-cooled. *Liquid-cooled engines* have

definite advantages in smaller frontal area and lower drag, which result in higher speed per horsepower. Owing to the small lateral dimensions and the flexibility of the cooling system, they can be placed almost anywhere in the airplane. As a rule, the liquid-cooled engine has a lower specific fuel consumption and oil consumption; however, there are a few disadvantages, *viz.*, the installation is usually heavier than for an equal horsepower of air-cooled installation, and the accessibility for service and maintenance is not so good. *Air-cooled engines*, on the other hand, have their own distinct advantages. They have a shorter crankshaft which cuts down the torsional and bending failures. They are lighter, owing to the elimination of the cooling system, and usually have a more efficient heat-transfer system.

Both the liquid-cooled and the air-cooled engines are made in a variety of shapes and vary in the arrangement of the cylinders about the crankshaft. The *radial type* is the most common air-cooled engine. The *V*, or *straight in-line, type* is the usual arrangement for liquid-cooled engines. However, both liquid- and air-cooled types are being manufactured in the V, W, and X types. These designations correspond to the letter of the alphabet that a front centerline view of the engine closely approximates.

Engine Parts.—The nose section of an airplane engine contains bearings which absorb the thrust of the propeller and reduction gears, usually of the planetary type. Nearly all engines of any power are geared. The gears are contained in the nose section. Gearing is efficient because it allows higher engine r.p.m. with accompanying lower propeller tip-speed. The mid-section of the engine usually contains all the parts necessary to an internal-combustion engine, such as cylinders, valves, valve mechanism, pistons, connecting rods, and crankshaft. The rear section of the engine may be considered as being composed of two parts. On engines having a geared supercharger, the section adjacent to the power section is known as the *blower section* and contains a centrifugal blower geared to the crankshaft. The rear part of the engine is devoted to attaching bosses and splined shafts for the attachment and operation of the accessories, such as starters, generators, fuel pumps, and hydraulic pumps.

Lubrication and Ignition.—Engine lubrication is accomplished in one of three ways, by the dry-sump method, by pressure-pump

method, or through use of a scavenger pump. The ignition system consists of magnetos, usually two or more coupled individually and connected to separate plugs in each cylinder so that higher fuel economy may result and so that, in the event of failure of either system, the other will still ensure operation. The booster coil is used for starting, for the magnetos do not generate a hot enough spark at very low starting r.p.m. High-altitude flying results in a corona discharge from the ignition lines; they must therefore be enclosed in an airtight harness which may be filled with an inert gas or operated under pressure. This type of operation requires the addition of superchargers in order that the engine may obtain sufficient oxygen for complete combustion of the fuel.

Superchargers.—Two types of supercharger are in general aircraft use: the single-stage supercharger, which may have a single speed or be adaptable to two speed operations to meet two altitude conditions, and the two-stage supercharger with an auxiliary stage which may be either gear-driven or turbo-driven from the exhaust gases. The power required to drive a geared supercharger is greater than that for the turbo-driven type, owing to higher frictional losses and to the fact that a great deal of heat is dissipated in the exhaust system and, with the geared supercharger, is completely lost. With a turbosupercharger this heat energy is transformed into rotational energy which, by means of the impellers, forces air into the carburetor system. The two types of supercharger have distinct effects on engine performance at altitude. A nonsupercharged engine has linear loss in power with increases in altitude. With the addition of a single-stage geared supercharger the horsepower-altitude curve is shifted, but the power loss with altitude has the same slope. If a two-speed single-stage geared supercharger is used, each speed of the supercharger will shift the power curve so that more power is available at higher altitudes, but the power loss per increment of altitude remains constant. Turbosuperchargers appear to give the optimum performance for all altitudes by providing constant-powered output for all altitudes from sea level up to the critical altitude of the engine-supercharger combination, at which point the power loss with additional increment of altitude will be the same as for a geared supercharged engine. The advantage lies in the fact that the turbo-supercharged

engine has an extremely high critical altitude which, through the use of two-stage operation, may be boosted as high as normal flight operation is desired.

Turbosuperchargers.—Geared superchargers with one or two speeds and one or two stages are well suited for flights at moderate heights or at one or two critical heights. But a properly designed turbosupercharger has a range of efficient operation from take-off to the edge of the stratosphere. Unfortunately, the most interesting details of its performance may not yet be published.

There has been a tendency for the operating altitude of certain types of military airplane to go steadily higher, and today it is essential that for these there shall be little falling off in engine performance in regions between 20,000 and 30,000 ft. There is evidence that the turbosupercharger preserves performance at these heights.

The power from an internal-combustion engine depends directly on the weight of the explosive charge that is taken in by the cylinders. This charge is initially air but is later combined with fuel in a way depending on the particular type of engine. The charge enters each cylinder during that part of the cycle of operations called *intake*. When the intake movement has been completed, the volume that the piston has displaced is expected to be filled with the charge. The heat energy generated by the ignition of each charge obviously depends directly upon the weight of the charge, all of which goes through the chemical process called *combustion*. Until a comparatively recent date, internal-combustion engines had to depend on the charge that normally entered the cylinder; if more power was wanted, the cylinder was made bigger. Then came the supercharger, its function being to crowd into the cylinder a greater amount of charge than would normally enter.

The supercharger is an air compressor attached to an internal-combustion engine and designed to fill each cylinder with a charge at a pressure and density greater than that which would have entered without its help. The weight of charge is increased nearly in proportion to its absolute pressure; thus the power output is correspondingly increased. The alternative is the much more expensive procedure of increasing the cylinder volume and, therefore, the weight of the engine in proportion to the increase of power desired.

On an airplane engine or any other internal-combustion engine a void is created within the cylinder as the piston makes the intake stroke, and the pressure of the outside atmosphere pushes a charge in to fill up the void. It is often said that the charge is "sucked" into the cylinder; but there really is no sucking, the only action being the pushing of the charge into the cylinder by the atmosphere. But this push is obstructed by the intake

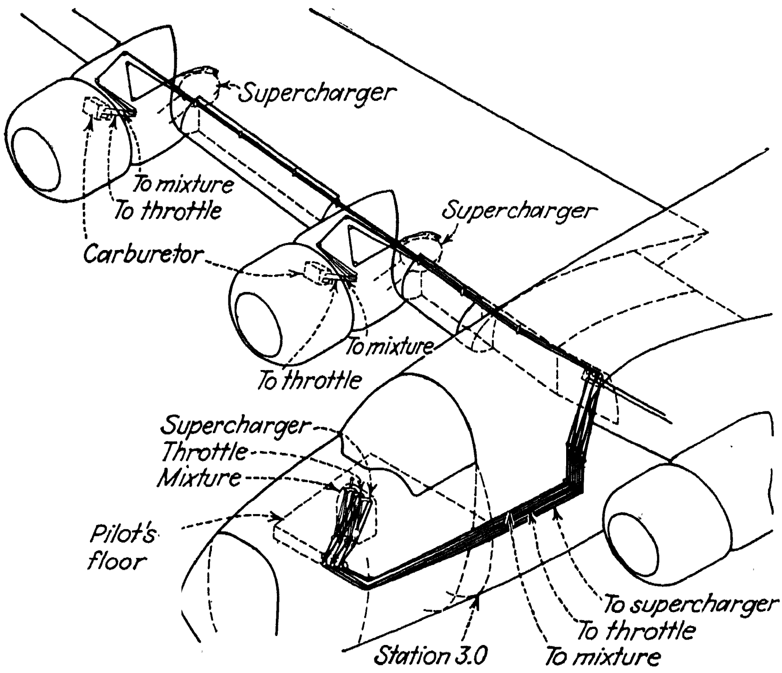


FIG. 2.—Engine controls on the four-engined bomber.

duct, carburetor, intake manifold, and intake valve. As the result of these obstructions and the lag caused by the speed of the piston, the pressure inside the cylinder is still below that of the atmosphere at the end of the intake stroke. Furthermore, all engine parts are hot, particularly the intake valves and the cylinder walls, so that the charge is heated as it enters the cylinder.

Therefore, when the intake valve is closed at the end of the intake stroke, the cylinder displacement is filled with a charge at a pressure below and a temperature above that of the outside atmosphere. The ratio of the weight of charge inside the cylinder

to the weight if the charge had been at atmospheric pressure and temperature is called *volumetric efficiency* and is from 75 to 85 per cent. That is, the weight of the charge is only about 80 per cent of the value corresponding to a cylinder displacement charged at atmospheric pressure and temperature. This applies whether the engine is at sea level or at height.

But, high up, the charge is still further decreased from the 80 per cent possible at sea level. The density of a cubic foot of air at average sea-level conditions is 0.0734 lb. But, at a height of 20,000 ft., it is only 0.0403 lb., which is about 55 per cent of the sea-level value. The engine power decreases roughly in the same proportion. At 20,000 ft. the power is 0.55×0.80, or 44 per cent, of the value that might have been obtained if the cylinder displacement were filled with a charge at sea-level conditions.

In the turbosupercharger the impeller is driven by a turbine wheel revolved by the engine-exhaust gases. The engine exhausts into a closed manifold where sea-level conditions are maintained at all heights. The exhaust manifold discharges into a nozzle box, which is immediately behind the turbine wheel. Modern nozzles usually cover the whole 360-deg. arc.

The nozzle box has nozzle openings exactly like those of a steam turbine, and these direct the exhaust gases against the vanes or buckets of the turbine wheel. This wheel is mounted on a shaft and drives an impeller, a centrifugal compressor, which supercharges the engine. The casing of the centrifugal compressor is an independent unit with provision for support of the nozzle box. This unit, comprising the centrifugal compressor and exhaust-gas turbine, is located on a convenient part of the airplane, with flexible connections to the exhaust and intake manifolds. The centrifugal compressor delivers air to the carburetor and then to the intake manifold.

As an airplane with a turbosupercharger climbs, automatic regulation keeps the pressure within the exhaust manifold and nozzle box at sea-level value. The pressure outside the nozzle box grows gradually less as the airplane flies higher. The difference between these pressures creates a stream of exhaust gas at a high velocity which turns the turbine wheel. This drives the centrifugal compressor and raises the pressure of the air entering the engine from the low value at altitude almost to that at sea level. Thus, in spite of the fact that the engine may be at a great

height (which would normally cause a big decrease in its power) the engine exhausts at sea-level pressure, receives it charge at approximately the same pressure, and continues to give sea-level power.

The first proposal for a turbosupercharger is believed to be that contained in a German patent granted to Reihm in 1911 for a four-cycle engine working at sea level. So far as is known, no practical use of the scheme was made at the time. In 1917, a French engineer, August Rateau, developed a similar plan for

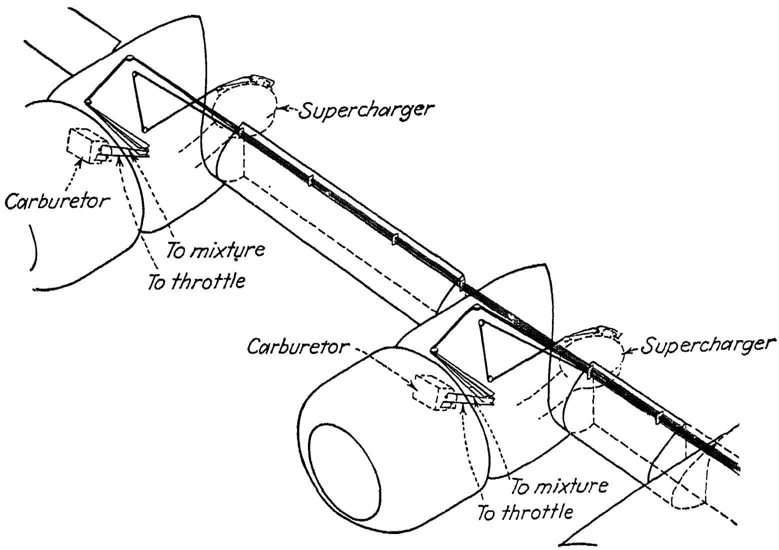


FIG. 3.—Engine controls at the nacelles and in the wing.

airplane engines and made a successful test with a dynamometer on a mountain peak in France. The First World War brought about the exchange of information between the Allies, and the Frenchman's scheme for a turbosupercharger was communicated to the N.A.C.A. in America. The N.A.C.A. asked the General Electric Company to undertake development work in the United States in cooperation with the engineers of the U. S. Army Air Corps at Dayton, Ohio. Thus was started an enterprise that is now showing good results.

This first turbosupercharger was tested at Dayton, Ohio, but the atmospheric pressure there was but little less than that at sea level. In the summer of 1917 an expedition had been sent to the

summit of Pikes Peak to test a Liberty engine at height. This engine was a 60-deg. V type, developed for general aviation use by United States engineers during the war. A similar expedition to Pikes Peak was arranged to test the turbosupercharger. The height at the peak was 14,109 ft. above sea level—much lower than the 25,000 to 30,000 ft. at which a turbosupercharger now operates. Nevertheless, the peak offered conditions for a general performance investigation.

At Dayton, the motor gave 350 hp.; at the summit, minus the supercharger, it gave 230 hp. After the inevitable delays a successful test was made with the turbosupercharger, and 356 hp. was obtained.

When the results of this test were reported, it was pointed out that, if the engine displacement were made large enough, 356 hp. could have been obtained without a turbosupercharger, but this unanswerable assertion failed to check work on the turbosupercharger. Shortly after the tests of Pikes Peak, the Armistice was signed and work on all war projects temporarily ceased. But an examination of the data available emphasized the need for continued development. The tests had shown the direction in which improvement was needed, and the supercharger was redesigned and installed in an airplane.

Then began a period of development and production by the U.S. Army Air Corps, the staffs of various aviation companies, and the General Electric Company. Soon evidence was forthcoming that the turbosupercharger could keep up sea-level pressure in the air-intake manifold up to appreciable altitudes.

Flight testing of the turbosupercharger from 1919 to about 1930 was largely confined to the making of altitude records. As a result, the world's record was held for various periods by the United States; but when it was found that an airplane at its maximum altitude devotes practically all its energies to keeping itself up and has little performance in other directions, the United States turned from record breaking to the improvement of performance at normal operating heights. Consequently, the world's altitude record passed to nations whose airplanes had no turbosuperchargers.

Rateau continued his development work in France during the First World War and after the Armistice. One or more squadrons of supercharged airplanes ultimately went into service, but

the French turbosupercharger was finally abandoned. Rateau, apparently, had not the manufacturing and technical resources of the engineers and research workers in the United States or the official backing of his government. He is alleged to have offered his design to the British Air Ministry; but it was not accepted, probably because it lacked durability in operation.

Turbosuperchargers were also made in England at one time, but apparently without significant result. Turbosuperchargers for Diesel engines have likewise been produced by the Brown-Boveri Company, and there have been reports that their principle was being applied to German Diesel airplane engines. Descriptions have also been given of Brown-Boveri turbosuperchargers on Otto cycle engines, in which the exhaust-gas temperatures are much higher than with Diesel engines; but there is no confirmation that these ever reached the production stage.

Aircraft Fuels.—The term "combustion" or "burning" is often used. In a chemical sense, it refers to the combination of one or more elements with oxygen, resulting in the formation of oxides of the elements accompanied by the liberation of heat. This heat, in the case of an internal-combustion engine, is converted in part into kinetic energy, or energy in motion. Oxygen is essential to combustion and is present in the air to approximately 20 per cent. The remaining 80 per cent is nitrogen. Nitrogen is an inert gas and does not enter chemically into the process of combustion. Oxygen is an active gas and will combine with a number of elements; in each case, the heat liberated will depend on the chemical nature of the substance involved. Hydrogen and carbon produce large quantities of heat when burned and constitute the most important fuels for the production of heat and power. Hydrogen is a light and inflammable gas. Carbon is a solid and exists in three forms, *viz.*, soot, graphite, and diamond, and in many chemical combinations. When carbon is ignited in a plentiful supply of air and oxygen, it burns with a clear flame and forms carbon dioxide (a harmless gas). When the supply of oxygen is insufficient, carbon monoxide will be produced. This gas is poisonous and will cause death when present in the air to the extent of only 4 parts in 10,000. It is odorless and colorless.

As fuels, hydrogen and carbon are seldom available in their natural state but occur in combination with other elements,

forming hydrocarbon compounds. There are many classes of these compounds in existence. Hydrocarbons are present in large quantities in petroleum, occurring as both liquid and gases.

Gasoline, or petrol, is a blend of various hydrocarbons and liquids ranging in boiling point from 90 to 425°F. When atomized, it vaporizes quickly. When mixed with air in the proper proportions, it forms a readily combustible charge. There is no isolated fuel that can be correctly termed "gasoline."

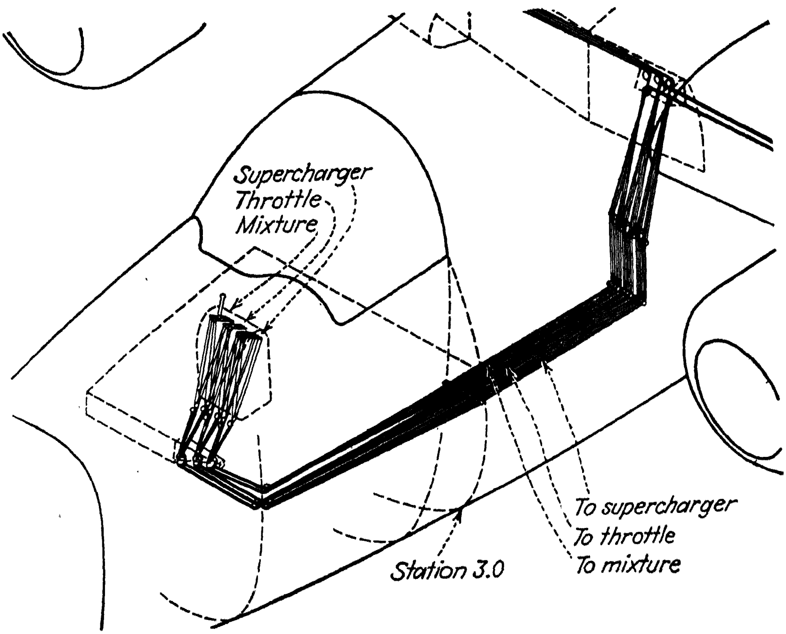


FIG. 4.—Engine controls in the pilot's enclosure.

Fuels fall roughly into three main groups, *viz.*, paraffins, alcohols, and aromatics. Gasoline is generally a blend of all three of these, with or without the addition of an antiknock agent.

The *paraffins* are a series of liquids and vapors including octane, heptane, and pentane and are the lighter products of the distillation of crude or mineral oils. The majority of the paraffins are characterized by a low antiknock value and a low specific-heat value, *i.e.*, the amount of heat given out by the complete combustion of a given quantity of the fuel. The blends of paraffins

generally used have a comparatively high boiling point (approximately 250°F.).

The *alcohol* generally used is *ethyl alcohol* or grain alcohol obtained by distilling wood, grain, sugar, etc., and is cheap to produce. It has a higher antiknock value but a low boiling point and low specific-heat value. Because the efficiency of an engine depends largely on the heat produced by combustion of the vaporized fuel, a high specific-heat value is essential. Alcohol also has a great affinity for water which causes corrosion and if it enters the carburetor can stop the engine. To prevent corrosion a capsule containing potassium dichromate is fixed in the bottom of the fuel tank to act as a corrosion inhibitor.

The third fuel is the *aromatic group* which includes *benzol*. This has a very high antiknock value but very low specific heat and boiling point. The aromatic group are the by-products of the manufacture of coal gas and until quite recently were lost as waste gases. A comparatively new process has been evolved called *hydrogenation* in which hydrogen gas is forced through a mixture of small coal and crude oil at a high temperature and pressure. From this process a good grade of blended aromatic fuels is obtained inexpensively.

It will be seen that for the best engine operation a fuel is required embodying points from all three groups. The ideal fuel has

1. High specific-heat value.
2. High antiknock value.
3. Medium boiling point (about 200°F.).
4. Low freezing point.

Unfortunately no single fuel fulfills all these requirements. Therefore, it is necessary to blend all three fuels in certain proportions. Too great a percentage of paraffin fuels, though giving good values for specific heat and freezing and boiling points, gives a very poor antiknock value. Too great a percentage of alcohol fuels gives a low freezing point, a fairly good antiknock value, but low values for specific heat and boiling point. Too great a percentage of aromatics gives a good antiknock value and low freezing point, but very poor values for specific heat and boiling point.

Additions of antiknock agents, such as tetraethyl lead, isopropyl ether, and iso-octane, raise the antiknock value of fuels to varying

degrees. Three cubic centimeters of tetraethyl lead added to 1 gal. of fuel will raise its octane rating from 10 to 18 points. Other factors affecting antiknock values are cylinder temperature, mixture ratio, compression ratio and boost pressure (raising which raises the cylinder temperature and promotes detonation), air-intake temperature, and cylinder-head design. Tetraethyl lead with or without other antiknock agents is found to be the most effective means of raising the octane rating of a fuel but gives

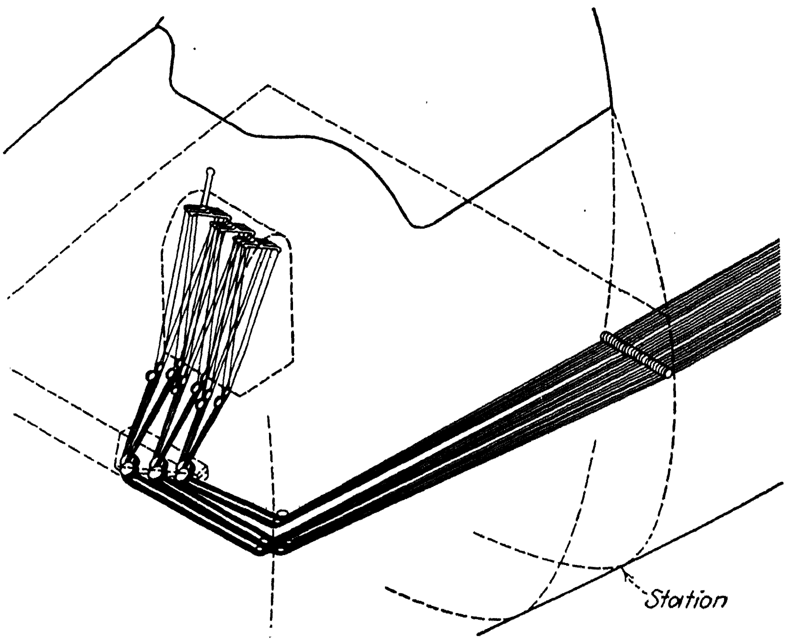


FIG. 5.—Engine controls on the pilot's pedestal.

rise to such problems as corrosion of head and valves, corrosion of exhaust, and leading-up of spark plugs.

Thus it can be seen that aircraft fuel is derived from the careful and calculated blending of different fuel groups with the addition of one or more antiknock agents. This fuel can be varied to give different octane ratings. The octane rating of a fuel is its antiknock value and is determined by comparison with a mixture of iso-octane, which has an antiknock value rated at 100, and normal heptane or normal pentane, both of which have antiknock values of 0.

The fuel to be tested is used to run a variable-compression engine in which the compression ratio is increased until steady knocking is produced. With the same setting, mixtures of iso-octane and either normal heptane or normal pentane are tried in the same engine until the same knocking occurs. The percentage of iso-octane in this mixture gives the octane value of the fuel.

Airplane Propellers.—Airplane propellers are chosen like all other components of the airplane to give maximum performance and yet meet with all the necessary operating and maintenance requirements.

There are three general types of aircraft propeller, each of which has innumerable modifications. *Fixed-pitch propellers* are the oldest practical type. The blades may be of wood, steel, aluminum alloy, Micarta, or other tough strong material. They may have a solid hub integral with the blades, or the hub may include provision for adjusting the blade angle while the ship is on the ground.

Constant-speed propellers have in the hub a mechanism controlled by a governor which adjusts the blade pitch so that engine r.p.m. will remain constant, regardless of power output or attitude of the airplane.

Full-feathering propellers include all the features of the constant-speed propeller, with a wider range of blade angles and provision for feathering, or turning, the blades to a position of minimum drag. This position enables the pilot to cut one or more engines on a long flight or in the event of engine failure so that the propeller will no longer rotate, resulting in increased range and, where engine failure has occurred, in a minimum amount of damage to the engine.

Both the constant-speed and full-feathering propellers may be driven by a hydraulic or an electrical system. As discussed in Chap. I on Aerodynamics and Preliminary Design, propellers must be chosen with a view to minimum tip speed, maximum efficiency, and proper clearance above the ground, water spray, or other obstacle likely to be encountered in normal operation of the airplane.

Propellers for small aircraft are usually two- or three-bladed types. In larger airplanes, four blades are sometimes used to give greater thrust for equal diameters. Several unusual designs

have been developed recently to meet the problem of propeller size.

Contrarotating Airscrews.—Rotol Airscrews, Ltd., has completed the development of a six-bladed constant-speed contrarotating airscrew. Although the airscrew has completed its bench tests, it has not yet flown owing to the fact that no standard type of British airplane engine has yet been adapted for its use. It is a well-known fact that increased engine ratings and greater full-throttle operating heights are making it difficult to absorb the desired powers with propellers of existing diameters. Taking the three-bladed propellers as an example, it is known that, when run at the correct tip speeds, required diameters increase by about 6 in. for each 2,000 ft. in full-throttle height; this situation, if reasonable ground clearance and landing-gear height are to be maintained, can be only partly remedied by widening the blades. The present tendency toward four-bladed propellers arises from the above considerations.

In view of the fact that tip speeds are limited to about 94 per cent of the local speed of sound, for highest efficiency, the spiral angle of advance is becoming high, and at speeds and full-throttle altitudes already contemplated this angle will reach a figure in the neighborhood of 55 deg. or more. Any airscrew having all its blades moving in one direction will have a large rotational component in the slip stream at a high spiral angle of advance, resulting in an ever-increasing drop in efficiency as the situation develops.

All these factors tend to favor the development of the contrarotating type. The design lends itself to the use of six or even eight blades of any given diameter. At the same time, straightening of the slip stream by the rear airscrew reduces the losses due to slip-stream rotation and should make possible the recording of satisfactory efficiency figures even at the higher spiral angles of advance.

The use of six or eight blades, particularly in a contrarotating design, has the further advantage that, under the conditions of great full-throttle altitude already mentioned, the best airscrew for maximum speed will also be very close to the optimum airscrew for take-off and climb. Other advantages in favor of the multiblade contrarotating propeller are the elimination of swing at take-off or when the throttle is opened or closed in the

of her exports went to the United Kingdom and 10 per cent to Belgium where it is very highly regarded for brewing purposes, because of its low protein content. This type of barley is not sought by Eastern maltsters in this country because of different brewing operations which favor a higher protein content in malt made from this grain.

The cultivated varieties of barley are included in four species (1) *Hordeum vulgare,* (2) *Hordeum intermedium,* (3) *Hordeum distichon,* (4) *Hordeum deficiens. Hordeum vulgare* is the six-rowed barley. Types of this species are used largely for feeds and malting purposes. *Hordeum*

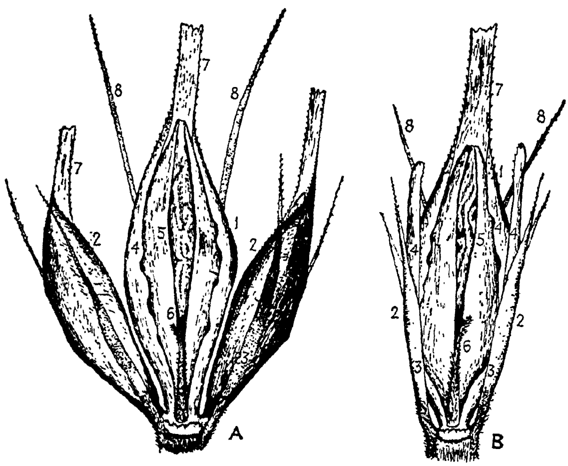


FIG. 14.—Spikelets from a single node of commonly grown barley.
A, Six-rowed barley (*H. vulgare*) showing median and lateral spikelets.
B, Two-rowed barley (*H. distichon*) showing median spikelet, and sterile lateral spikelets.
1, Median spikelet; 2, lateral spikelet (sterile in two-rowed barley); 3, outer glume; 4, lemma; 5, palea; 6, rachilla; 7, main awn (broken off); 8, awn on outer glume. (*T. A. Stoa, Varietal Trials with Barley, North Dakota Bulletin* 184, 1924.)

distichon is two-rowed barley, having softer plumper kernels which are suitable for some types of malt.

The varieties of barley commonly grown include Manchuria, Oderbrucker, Odessa, and O.A.C. 21. The first is grown mostly in western Minnesota and North Dakota; Oderbrucker is most popular in Wisconsin and Illinois; Odessa is grown mostly in South Dakota, and O.A.C. is the more prominent Canadian variety.[1] Of the two-rowed barleys, the Spartan variety is grown in Michigan and Alpha in New York, while in the Northwestern great-plains area Chevalier and Hannchen are raised. A relatively recent variety, Trebi, has gained considerable usage in Idaho and the Dakotas. In the Pacific coast states, the most prominent varie-

[1] HARLAN, H. V., *U. S. Dept. Agr. Farmers' Bull.* 1732, 1934.

table to service types of engine. Provision is made for a cannon to be fitted to fire through the shaft.

Pilots who have flown behind the Fairey airscrew have been impressed with its performance. They have all found that rudder, elevator, and aileron control has been much more positive in operation than with the conventional one-way propeller. The contrarotating propeller has been produced for approximately the same weight as a single airscrew absorbing the same engine power.

New De Haviland Airscrew.—The De Haviland Company has produced two new types of propeller, contrarotating and four-bladed.

The first of the four-bladed series was to suit the engines of 2,000 hp. and higher now in use. It has a maximum diameter of 16 ft. The four-bladed propeller embodies the same mechanical principles as those of the earlier De Haviland types. The blades are made of aluminum alloy as before. These blades have proved exceedingly efficient. Over 80 per cent of the blades damaged by forced landings, crashes, or gunfire have been repairable.

The contrarotating propeller has three blades in each plane. The same mechanical operating and construction principles are employed as in the four-bladed type. This propeller is being made in varying sizes to keep pace with the development of modified engine reduction gearing.

Final Design Problems.—After the selection of engines and propellers for a given airplane, it is the aim of the installation designer to obtain as nearly as possible the same operating characteristics and horsepower output in the completed airplane as were obtained in the laboratory tests. The problem is a complex one. Completion of detailed studies of the engine mount, cowling and nacelles, fuel system, oil system, induction and exhaust system, engine controls, ignition system, and the installation of engine accessories, even the engine mount, which, offhand, would seem the simplest problem, has many complications. Such features must be included as provision for accessories, quick engine change, and a high strength-to-weight ratio.

Much of the weight of the *engine mount* may be saved by employing monocoque construction which utilizes the outer ring space of the nacelle as a structural stressed-skin member. This structure may also be used in part to form the oil tanks,

excess weight thus being further eliminated. This arrangement is practical only where the complete structure is large enough to permit the entrance of the mechanic; even then, it is complicated if ducts, intercoolers, and accessories are not installed so as to leave ample space.

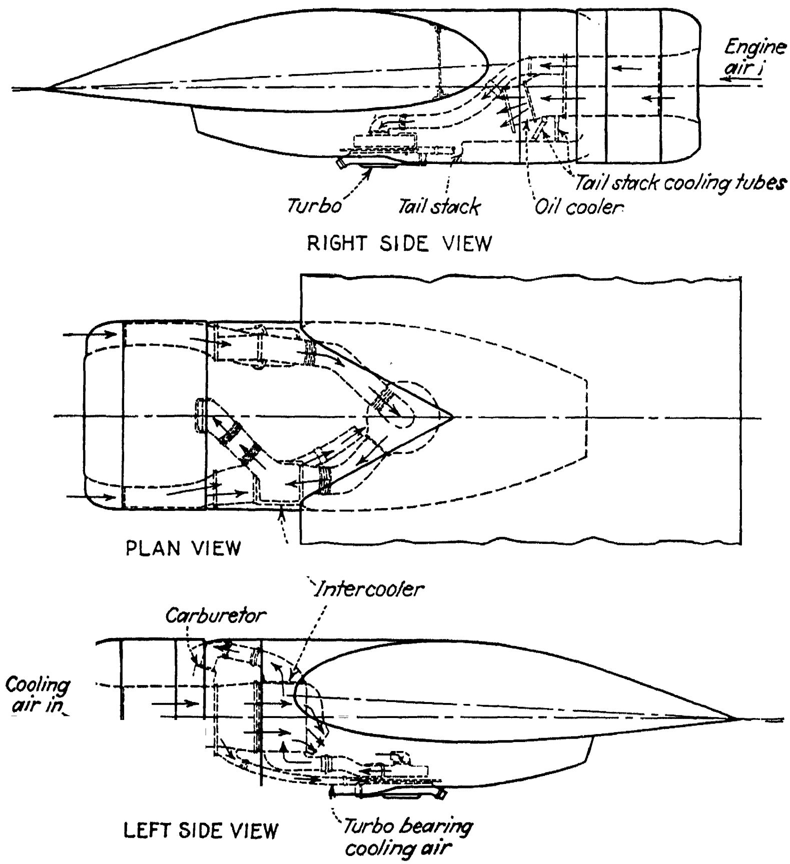


FIG. 6.—Turbo supercharger installation for a radial engine.

The most widely used engine mount is of welded-steel tubing in the form of a complex truss. The mounting of the engine to its mount is accomplished by means of rubber bushings or flexible pedestals, which allow the engine vibration to be absorbed to a great extent before transmission to the airplane structure.

The engine *cowling* and *nacelle* are usually divided into two sections, the engine cowl being that portion which covers the engine proper and attaches directly to it and the fixed nacelle being wholly or in part an extension of the airplane or wing structure.

The N.A.C.A. as a result of continued research and testing has developed a type of cowl that gives lower drag and better control of cooling. The pressure drop through the engine cowl should be 4 to 6 in. of water, depending on the operating conditions. The juncture between the engine cowl and fixed nacelle is provided with a slot through which the cooling air may exhaust. In smaller airplanes the slot is usually fixed. Where larger power plants are employed, a variable slot must be provided so that the rate of flow of cooling air may be varied to suit operating temperatures. The slot area may be changed by use of flaps operated mechanically, hydraulically, or electrically, by means of a sliding skirt or through the use of a nose slot to give a reverse flow. Air intakes, or scoops, must be provided in the cowl or the nacelle to provide constant flow of air to the carburetor intake or to the induction side of the supercharger.

Fuel systems for airplanes are as different in design as are the airplanes themselves. However, there are certain basic considerations, no matter what the final design. Fuel tanks may be an integral part of the structure of the wing, hull, or floats or may be separate removable tanks installed wherever space is provided. Fuel lines must be of a size and arrangement suitable to the engine and to the operating conditions for which the airplane is intended. Flowmeters of the displacement or rotometer type must be included in the fuel system. As an auxiliary to the engine-driven fuel pump, hand pumps or electric booster pumps must be provided in the design.

Oil Tanks.—It is usual to allot *oil capacity* in proportion to fuel capacity. For air-cooled engines, 1 gal. of oil for each 11 gal. of fuel should be provided. For liquid-cooled engines the ratio is 1 gal. to 15. A hopper must be included in the oil tank so that hot oil returning from the engine may be segregated to minimize foaming and fuming; suitable vents to take care of this and to control temperature changes must be installed. In the oil-return line, oil coolers are also required to give proper heat dispersion.

The coolers must be provided with shutters, having pressure control, thermostatic control, or viscosity control.

The *air-induction system* on the complete airplane is always the result of lengthy flow tests and engine-running tests. For engines with two-stage superchargers the induction system must include intercoolers to dissipate the adiabatic heat of compression of the air leaving the first supercharger. The system of ducts on such installations becomes quite complicated, owing to the cramped space in which it must be placed.

The *exhaust system* must be designed to withstand engine vibration, heat, and pressure. Nearly all such installations on modern engines have a collector ring or manifold which delivers all the hot gas to a single outlet, whether the design be for turbo-supercharger or not.

Recently much investigation has been directed toward the use of the waste heat in the exhaust gases in a jet to gain a small thrust increment.

Jet Propulsion.—Some interesting information has come to hand in respect to an aircraft that employs *jet propulsion* as a further means to economic efficiency.

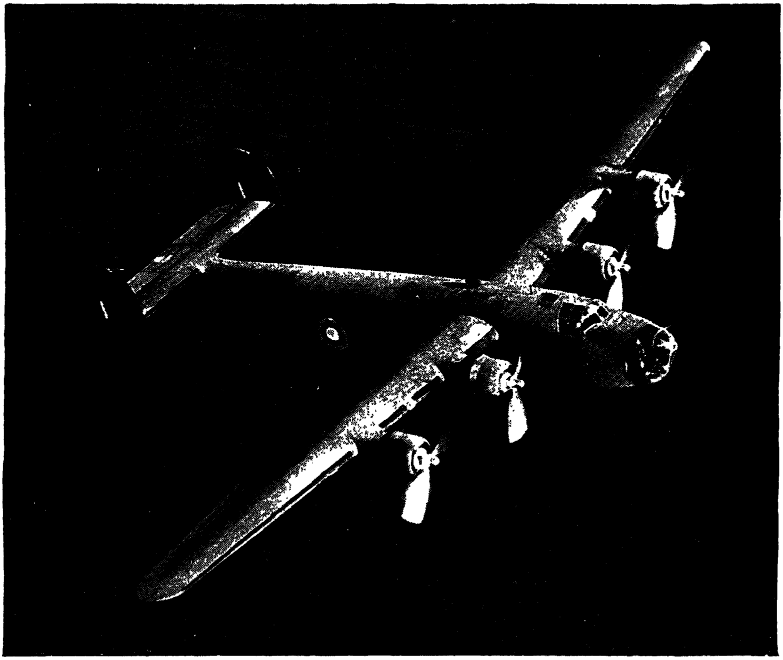
A nozzle duct runs along the entire length of the fuselage. In the forward portion of this duct a blower driven by the engine produces a pressure increase which creates an air flow towards the aft portion of the duct. The flow first cools the engine and then joins the exhaust gases. This procedure increases its thermal value and makes possible an expansion toward the exit nozzle. The expansion can be intensified by the injection of fuel which is ignited in the vicinity of the exit nozzle. The thrust needed for the airplane is therefore created by the blower on the one hand and by the expansion of the air and gases situated behind it on the other. By adjusting the diameter of the duct, the pilot is able to control the jet.

By this means, part of the energy lost through engine cooling and in the exhaust can be recovered. This type of propulsion reveals its advantages particularly at speeds approaching the velocity of sound. As a rule, the speed of the air flow at the blower intake is lower than the flying speed; therefore, the impeller blades can operate at a higher degree of efficiency than the airscrew blades of conventional airplanes.

An interesting development (though purely incidental) is the application of this principle to bombs and ammunition. Even bombs of the heaviest calibers are not powerful enough to pierce the heavy armor of capital ships upon impact; but in the near future, perhaps sooner than is generally assumed, it will become possible to increase the power of the falling bomb by means of jet propulsion created by a rapidly expanding gas. If by this means the velocity of the bomb can be increased by 50 per cent, its power upon impact will be doubled. Once a few hundred pounds of high-grade steel has pierced the ship's armor, owing to its velocity of between 1,000 and 1,140 ft. per min., and has attained the interior of the vessel, only a few pounds of high explosive will be required thoroughly to destroy any type of armor.

The *engine controls* designed by the power-plant group include throttle mixture, cowl flaps, propeller governor, supercharger, and oil-cooler shutters. These controls should be made automatic insofar as is practical in the airplane so that the human element in flight can be minimized.

In addition to the propeller, *engine accessories* include many other items, most of them electrical. Starters may be electric or hand-cranked inertia types or of the cylinder-expansion type. The latter may be a compressed-air charge directed to the cylinders in their firing order or an expanding charge of gas resulting from an explosion in a cartridge. Generators on modern aircraft engines must bear a heavy load owing to the complex radio, armament, and flight-control equipment. Other electrical accessories for the engine include cylinder temperature indicators, tachometers, fuel-analysis indicators, fuel and oil pumps, and pressure indicators.



Consolidated *Liberator* for Great Britain. (*Photograph by Otto Menge.*)

CHAPTER III

CONTROL-SURFACE DESIGN

The work of the control-surface group must be coordinated to a marked degree with that of the aerodynamics, wing, and structures groups, so that the performance of the airplane will meet the service requirements.

Responsibility of the Group.—The responsibility of the group is to take the general dimensions of the surface controls as specified on the preliminary three-view drawing and from them create the design of the flaps, ailerons, tabs, and empennage. In conforming to these requirements, it is also their responsibility to produce working drawings that will enable the shop to produce the parts in quantity, at a minimum cost.

Generally speaking, though they differ slightly from one model to another, the parts of the airplane the group is responsible for are

1. The empennage, which comprises the complete tail-surface assembly, stabilizer, elevators, vertical stabilizers, and rudder.

2. Everything aft of the rear spar of the wing, removable trailing edges, flaps, ailerons, trim tabs, and aileron cutouts.

Control Surfaces and Their Functions.—An explanation of all control surfaces and their flight functions is necessary so that an understanding of the requirements for their design can be reached.

The purpose of control surfaces on an airplane, assuming a vertical turning axis, a longitudinal rolling axis, and a transverse pitching axis, is to produce static stability about the three axes in all flight attitudes and under all loading conditions. Attainment of this stability is a prerequisite to the desired control of the ship in maneuvers.

Their purpose is also to produce ample control over the attitude and motion of the airplane in flight, for ease of handling in aerobatics and premeditated changes in attitude or for return to normal flight subsequent to gust action.

The controls must have moderate forces so that they can be operated without undue effort or fatigue by the average pilot. A degree of sensitivity is important, depending largely upon the basic mission for which the airplane is designed.

They must have provision for control over trim so that shifts of center of gravity, due to fuel consumed or bomb loads dropped, will not require constant correction by primary surface controls.

Provision must be made to avoid flutter through careful designing so that the natural frequency of the control-surface structure lies outside the range of the imposed aerodynamic oscillations.

Empennage.—1. The *empennage as a whole* is what directs the pitching or diving and turning or yawing of the airplane. This tail-surface assembly acts like feathers on an arrow during flight.

Trim tabs mounted at the trailing edges of the elevators and rudder provide movable surfaces to adjust the forces to produce the necessary ease and range of control.

2. The fixed horizontal tail surface to which the elevators attach is the *stabilizer*. It produces most of the stability for

pitching moments and controls the plane in entry to or recovery from a dive.

3. The *elevators* control dive and climb.

4. The fixed vertical tail surfaces to which the rudder attaches are the *fins*. They produce most of the directional stability and act like the keel of a boat.

5. The *rudders* produce control around the axis of yaw and thus direct turning or directional control.

Surfaces Aft of Rear Spar of the Wing.—The *ailerons* are hinged portions of the trailing edge of the wing, usually near the tip. They are balanced statically and dynamically about their hinge lines.

The ailerons produce roll by increasing the camber of the wing section on one side of the ship and decreasing it on the other. A by-product of roll is yaw. The aileron in increasing the effective wing camber also increases the drag on that side and thus causes the ship to turn. The frise nose balance adds corrective yaw by "venting" the air flow about the aileron and making the drag on each side equal.

Dihedral produces lateral stability by making the lift on the low wing greater than that on the high wing and thus righting the ship.

The movement of one surface produces an effect on the other two surfaces by changing the air flow about it and changing its attitude with respect to the relative air streams. Thus, due to dihedral, the rudder produces roll by advancing one wing faster than the other and thus increasing its lift.

Roll will produce turn with a fixed rudder, for the air flow will be faster over one side of the rudder than the other. Thus, reversal of controls in steep turns may become necessary in order to maintain stability.

The need for light control forces is obvious. Many schemes for reducing required forces are in use.

Aerodynamic balance is achieved by the use of aerodynamic forces on a part of the surface ahead of the hinge line to counteract those acting aft.

Balancing tabs are small hinged surfaces attached to the control surface to act as corrective or differential forces to correct for trim, and for directional discrepancies.

Servo-tabs are tabs connected by cams or levers to the primary control to give percentage corrections. They are sometimes

connected by a differential control to give a balancing effect as well.

Power boosters are sometimes connected to lighten the control forces.

Trim tabs (usually mounted on piano hinges) produce fine adjustment of the control surface so that no force is required on controls. They are used in place of the primary controls on long flights where only minor deviations in direction, climb, etc., are required.

The adjustment is in the cockpit; thus, the pilot may make corrections as required in flight. The system must be rigid so that small amplitude vibrations may not be set up and amplified in the primary control. The system must be irreversible also, so that aerodynamic force will not tend to change its setting or adjustment.

Mass balance is used in structures in which the surface mass cannot be distributed about the hinge line sufficiently. Static balance is obtained in these cases by adding weights at one end of the structure. Dynamic balance must also be achieved so that flutter will not occur.

The axes of vibration, product of inertia, method of accomplishing complete dynamic and static balance, are all vital factors in reducing control forces.

For the airplane to move efficiently in flight, it must have less wing surface than that required for take-off. Thus, various types of flaps have been developed. Those which increase the lift by a change in the effective airfoil camber only are called *plain flaps*. Plain flaps are located from the side of the fuselage outboard to the inboard end of the aileron and, in fact, are similar to the aileron except in operation. They are connected so that they depress together on both sides. As they are lowered, they produce lift by increasing the camber, but they do not add to the total wing area. This type of flap produces drag with increases in lift and is usually employed on smaller airplanes in which the drag is not too important. The plain flap also produces a large diving moment by placing the center of drag below the chord plane, a condition requiring correction by the elevators.

Fowler flaps are a more efficient type in terms of the ratio of increased lift over increase in drag. The Fowler flap is much

more complex than a plain flap, but with careful design the weight penalty is usually cut to a justifiable minimum. It is also more effective, for it increases the area of the wing while adding to the camber and effective chord length. It produces the change in camber less abruptly than the plain flap does. With proper arrangement, it does not disturb the balance due to down-wash striking tail. This is a function of empennage location as much as anything else, and the ship should be designed from the first with the flap in mind.

Other flaps are modifications of the above, as a rule. The *split flap* is a hinged type in which only the lower trailing-edge surface is hinged downward. The *zap flap* is a "ventilated" split flap.

Flaps of the Fowler and other extensible types are of airfoil section. Thus, they add lift with a minimum increase in drag.

Trailing-edge structures are often built as detachable units of lighter construction than the main wing panel. They take none of the wing bending loads. Over the aileron the trailing-edge section merely acts as supporting structure for its hinges and fairing for the aileron leading edge. The trailing edge over the flap has the same function as at the aileron, modified by the type of flap.

DESIGN PROBLEMS

From the foregoing, it may be seen that the design problems are numerous and complex.

Fins and Stabilizer.—The construction of the fins and stabilizer must be extremely rigid so that no vibration will be imparted through the hinges to the rudder or elevator.

The *loads* imposed on them are as follows:

1. Beam bending, due to the loads acting normal to their axes.
2. Chord bending, due to drag forces parallel to the time of flight.
3. Torsion, due to slip-stream differential forces from one side to the other.
4. Fin loads on the stabilizer for twin vertical surfaces, where the fins are mounted at the stabilizer tips. These add bending moments to the stabilizer and add to the chord bending.
5. Shaking forces, due to fuselage flexibility and whipping action.

Many *types of construction* are employed to gain the required strength. Stressed skin monospar types with and without stringers are used. Those with stringers require a lighter spar. Either type can be designed very efficiently. Stressed-skin two-spar types, with and without stringers, are usually of the "box-spar" type in which the two spars and upper and lower skins form a beam of high sectional qualities. Various multispar types have been used in which the number of bulkheads or ribs usually varies inversely as the number of spars.

Care must be taken in designing so that a careful weight saving in a surface will not mean a penalty in attachment. The stabilizer-to-fuselage connection is usually effected by means of four bolts through spar fittings into fuselage forgings. The fin-to-stabilizer connection can often be made by using integral spar construction and skin attaching strips or angles. Hinge attachments are best when in line with bulkheads to distribute the load out to the skin.

The use of minimum gauges is desirable, but within limits set by practical considerations. With very thin sheet, difficulty in handling in the shop results in poor production and unavoidable damage. The stiffness vs. strength requirements call for very close spacing of the bulkheads when minimum gauges are used, or a great number of stringers.

Elevators, Rudders, and Ailerons.—The construction of elevators, rudders, and ailerons is an entirely separate problem, because of special conditions and requirements.

1. The *loads* imposed on these parts require that they be stiff in bending so that they will not fail at high angles or speeds. Owing to the fact that the control force from the pilot is applied at one point on the surface and must be reacted over its whole length, they must be torsionally stiff. The need for stiffness is obvious; deflections would result in loss of control or in periodic vibration or flutter.

2. Another factor to be considered is *arrangement for proper movement* for ease of control. Locate the hinge line to give the required aerodynamic balance. See that proper clearance exists in all positions of the surface, so that in extreme positions it will work easily and without interference.

Construction.—As usually constructed, the movable control surfaces constitute the lightest exterior construction on the

airplane. The *nose section,* or leading edge, of the surface is usually a sheet-bulkhead combination forming a torque box. This section is interrupted by hinge cutouts to accommodate the hinge brackets from the fixed surface. The need for stiffness was described above. Much of the bending is taken by the fixed surface, but being hinged all torsion must be taken by the movable surface.

Aft of the hinge line, the *trailing-edge structure* consists usually of light ribs covered with fabric. A good grade of cotton fabric is still used for lightness, enough ribs being used to maintain the external shape. Owing to "doping," bracing for fabric tension is necessary to avoid collapse of the structure as the fabric tautens.

Trim, Servo-, or *balance tabs* are usually mounted on small beams between ribs, with a control rod or tube running to the fixed surface. The need for lightness is paramount since they are farthest from the hinge line and produce a large moment. The need for stiffness is also great, so that their deflection will not induce flutter.

Mass balance is employed because the light type of construction puts too much weight on the wrong side of the hinge line. The weight must be secure so that it will not magnify any stray vibrations and work loose. Such vibrations may crack the thin skin of the box beam or torque box.

Controls.—The controls that actuate the control surfaces are very specialized in design and involve many considerations. Because flight involves control in three dimensions, flying is more like riding a bicycle than driving a car. Lateral stability must be maintained. There can be no backlash or play in controls because an airplane moves so fast that corrections from one direction to its opposite must be instantaneous. Friction must be minimized so that the control forces at the wheel will not be too large. It is necessary to keep deflections low; thus, reversal of direction can be made quickly, and flutter will not ensue.

The *elevator controls* run from the wheel, or "stick," back to the elevator. They are composed of a torque tube, to the interior of the fuselage, which is an extension of the elevator spar, or torque box. On this the torque-tube horns inside the fuselage act as bell cranks to which the cables from the cockpit

attach. Suitable guide and corner pulleys are installed over the length of the cable.

The *rudder controls* run from the rudder pedals to the rudder horns in or near the stabilizer at its center. They are the same as the elevator controls for a single rudder in which the rudder spar, or torque box, extends down into the fuselage. The installation is more difficult for twin rudders, for the movement must be transmitted from the stabilizer tips to the center line. Interference between rudders and elevators is eliminated by clearance cutouts in one or the other so that both may have full motion.

The *aileron controls* may be cable- or torque-tube-operated. Because rolling motion is small, they should be sensitive and positive. They should have the least control force to ensure sensitivity; therefore, they need the most aerodynamic balance, but because of their shape and location they are most susceptible to flutter.

The available space for controls is generally small and congested; thus, the torque tube, or cables, must be carefully located. The controls must flex with the wing without producing movements of the surfaces, and therefore any stretch on the cables must be balanced out.

The *tab controls* may be similar to the aileron control out along the spar. From the spar to the tab itself, there are different systems. A screw arrangement can be driven by a gearbox operated by the torque tube, or cables. This extends or retracts a push-pull tube. An electric-motor arrangement can replace the cable drive.

Control surface locks are necessary for ground handling so that when the ship is "staked out" the hinged lightweight surfaces will not be damaged from wind on the ground.

For safety at take-off to obviate the possibility of their being forgotten, control surface locks should be designed so that the ship cannot be taken off with the locks engaged. Various yokes and bars are used, to lock the wheel across the pilot's seat so that he cannot sit down before removing them. Locks consist of pins engaging some part of the mechanism near the movable surface, locking it near the source of the load to prevent strain and shaking of the control system.

Flaps.—The design of flaps involves a combination of the requirements for fixed and movable control surfaces.

Plain flaps are most similar to ailerons and have no special problems of design. The loads imposed on them are torsion and bending between hinge points. They are similar to ailerons in construction and loading. They are controlled by a linkage arrangement, operated through cables running "around" the system and motivated by a hydraulic cylinder, or by a torque-tube system controlled by a screw arrangement.

Fowler flaps are more complicated in design and operation because they move aft and down as they turn. The loads imposed on them are similar to those on a wing supported at several points corresponding to the track points. The design is difficult owing to the shallow spar, necessitated by the thin section required. Therefore, all-metal construction for maximum stiffness is mandatory; at that, the whole flap assembly is a very thin beam. Because of the large loads, then, frequent supports are necessary to keep the bending moments within the allowable for the beam properties of the flap. Curved flap tracks as a means of obtaining movements are, as a rule, better than a complicated linkage system and give more rigidity. In shaping these tracks, the arc of a circle is simplest for practical shop reasons; by using a large radius, it can be made to work. Other shapes may be desired to give special travel patterns but should be avoided if possible.

The sources of *flap control power* may be one or a combination of the following: Hydraulic actuation is accomplished through a hydraulic cylinder connected to one end of a "run-around" cable system. Electrical operation may be by means of a gear-box-operated screw or electric-operated individual hydraulic unit. Hand (emergency) operation consists in a torque-tube drive to the screw (in the electrical type) or a hand-operated hydraulic pump.

Trailing Edges.—Trailing-edge construction is quite light. It bears no major loads, and its main function is as fairing for the main wing structure. It sustains a light load and no wing bending, owing to its small area and flexibility. The trailing-edge construction is usually a set of ribs tied together by a V section aft and an attaching strip top and bottom to match the rear-spar flange angles where it is bolted on. Hinge brackets for the ailerons are continuations of the main-wing bulkhead structure including lateral stiffeners.

CONCLUSION

General advice to the control-surface engineer may be summarized as follows:

Avoid engineering errors due to poor judgment or calculation. Avoid errors in layouts, due to carelessness or inaccuracy; mistakes in layouts and interferences are difficult to detect when three dimensions are involved but must be found before the drawings are released. Bad judgment is usually a result of inexperience or hasty decision without consideration of all the factors.

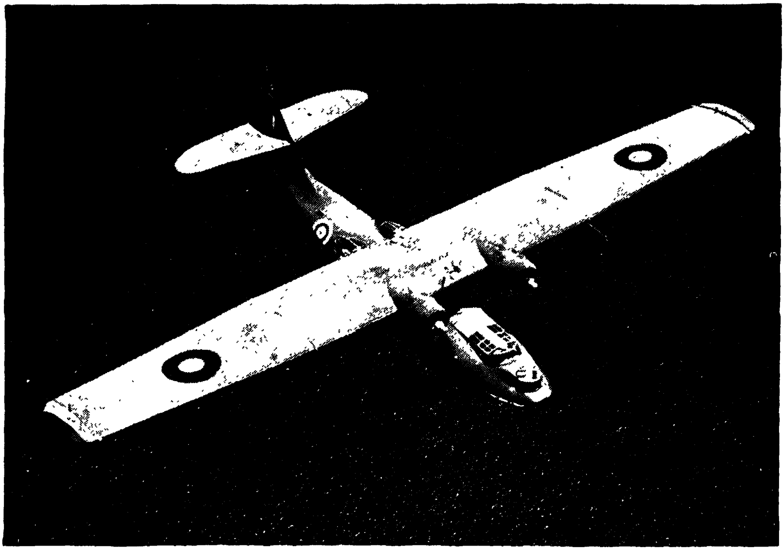
The danger of inadequate clearances cannot be overemphasized. An interference in a control surface may cause a crash. Insufficient edge distance for rivets is inexcusable in any phase of airplane design. Inadequate allowance for misalignment is a too-common error—remember the properties and functions of the parts you are designing.

Errors in drawings are due to poor drafting and should be easily detected. See that there are no incorrect views to confuse the shop. Do not pass on incorrect dimensioning. Be sure that the bill of materials is correct, to prevent loss of time.

Shop errors are the responsibility of the engineer unless the above precautions have been observed. Even then parts made incorrectly may turn up now and then. Parts made inaccurately may be reworked to within the allowable tolerances.

In general, remember that two things cannot be in the same place at the same time; watch your layout for interferences and clearances. Allow plenty of leeway for misalignment. Sometimes a little adjustment can save a lot of time and money. Allow plenty of rivet-edge distance for strength. Make tolerances as large as possible to help production. Hold tolerances close only when necessary to get proper functioning of parts, necessary fits, and good operation.

Be dependable. Check your drawings so that you know that they are right before you release them. Work steadily, not frantically. Keep busy, but do not rush through the job, hitting only the obvious high spots.



Consolidated *Catalina* for Great Britain. (*Photograph by Otto Menge.*)

CHAPTER IV

WING STRUCTURE

PRELIMINARY DESIGN AND GENERAL ARRANGEMENT

Types of Wing Structure.—For the benefit of those who are unfamiliar with airplane types, a number of typical wing-structure arrangements will be briefly described.

Figure 1-*a* shows a biplane. The wing structure consists of lower panels, center panel, upper outer panels, and interplane bracing. Interplane bracing includes N struts, cabane struts, cabane wires, and landing and flying wires. Biplanes have been almost entirely replaced by the cleaner and more efficient monoplane.

Figure 1-*b* shows an externally braced high-wing monoplane. Streamline struts carry wing loads to the fuselage. Small jury struts are used to reduce the column length of the lift struts when they are loaded in compression. Many light sport planes use this form of structure.

Figure 1-*c* shows the high-wing cantilever monoplane. The wing structure is entirely contained in the wing envelope.

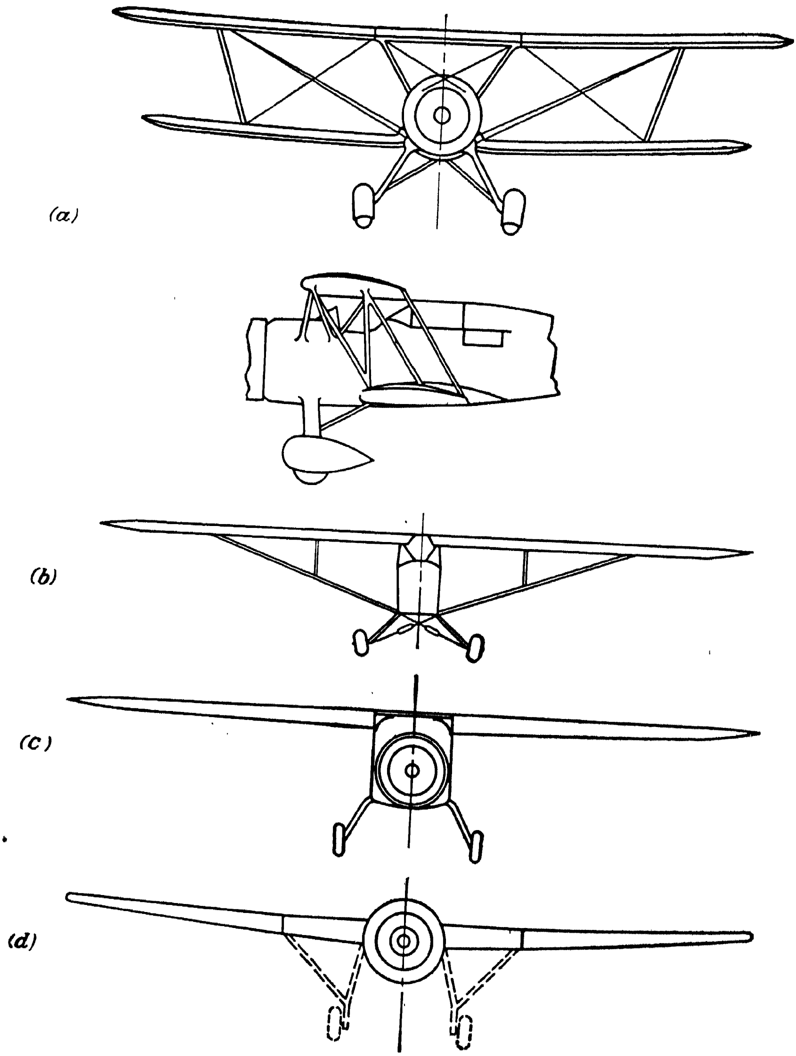


FIG. 1.—Wing arrangements.

Figure 1-*d* shows a midwing cantilever monoplane. The wing structure is carried through the fuselage.

Figure 2-*c* shows the low-wing cantilever monoplane. The wing structure is continuous across the fuselage. Many modern high-performance airplanes are of this type.

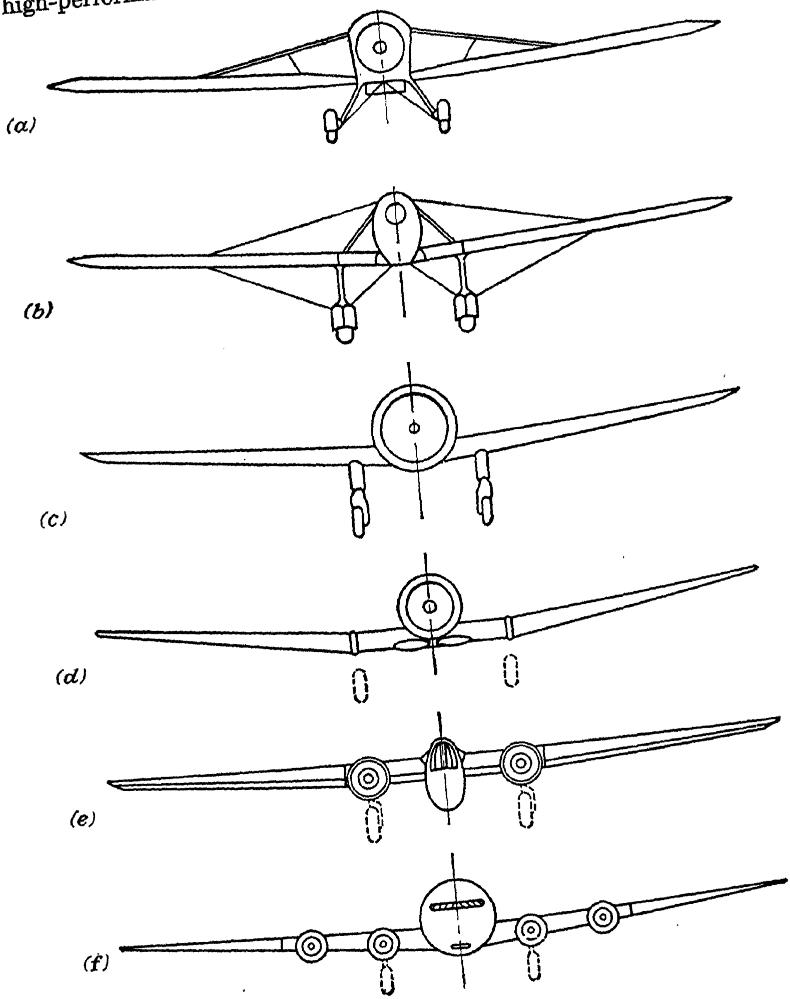


FIG. 2.—Wing arrangements.

Figure 2-*b* shows an externally braced monoplane using flying and landing wires. Landing-gear loads are brought into the wing and carried by diagonal struts to the fuselage.

Figure 2-*d* shows a low-wing cantilever monoplane built with a center section and outer panels.

Figure 2-*f* shows a similar type with four engines.

Flying-boat and float-seaplane wing arrangements require provisions for lateral support on the water. This is accomplished

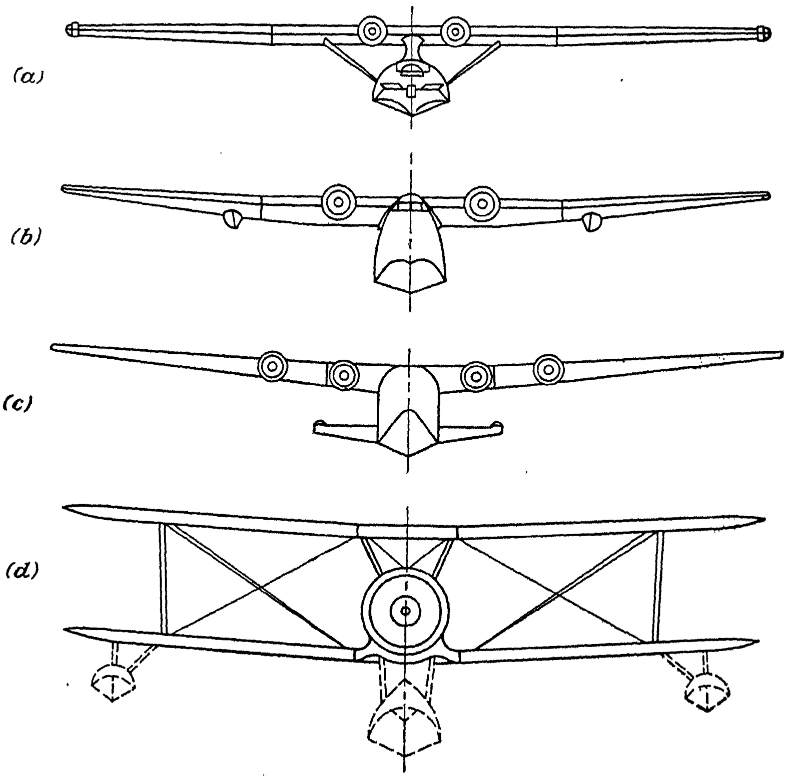


FIG. 3.—Flying-boat and seaplane wing arrangements.

by the use of fixed-wing-tip floats, retractable wing floats, or hull sponsons.

The structure must also be designed to prevent damage due to heavy spray in landing or take-off. In the case of flying boats, wings are mounted high on the hull to give propeller and flap clearance over the water.

Figure 3-*a* shows a semicantilever flying boat. The center section is attached to a hull superstructure and, to lift struts, outer panels carry retractable wing-tip floats.

Figure 3-*b* shows a flying boat with full cantilever wing and wing floats, retracted into the lower surface of the outer panels.

Figure 3-*c* shows a flying boat using hull sponsons for lateral stabilization on the water.

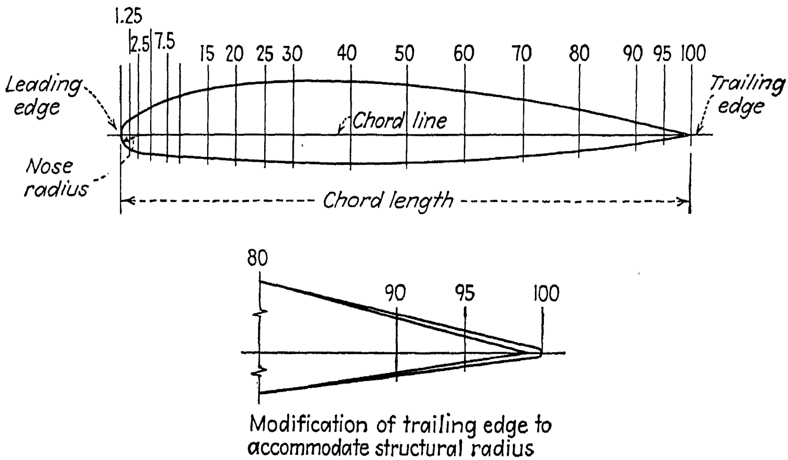


FIG. 4.—An airfoil section showing dimensioning.

Stations, per cent	Stations, in.	Ordinate, upper, in.	Ordinate, lower, in.
0	0	0	0
1.25	2.25	4.2552	−3.8016
2.50	4.5	6.0696	−4.7520
5	9	8.7048	−5.8969
7.5	13.5	10.6704	−6.5448
10	18	12.3336	−6.9984
15	27	14.7312	−7.4952
20	36	16.3080	−7.8192
25	45	17.3016	−8.0136
30	54	17.7552	−8.1864
40	72	17.5392	−8.2944
50	90	17.2864	−7.9056
60	108	14.1696	−7.0848
70	126	11.5334	−5.8752
80	144	8.3376	−4.3632
90	162	4.4900	−2.4530
95	171	2 3200	−1.3340
100	180	0	0

Figure 3-*d* is a single-float biplane seaplane. Latest designs of this type are monoplanes.

Envelope Shape of the Cantilever Wing. *Airfoil Section.*—All wings have a cross-sectional outline so shaped as to give large aerodynamic lift with small drag. This shape, or section, is called an *airfoil.*

Figure 4 shows an airfoil and the method of defining its shape. The table gives ordinate stations in percentage, stations in inches, and upper and lower ordinates in inches.

In laying out the section the chord line is first laid down, stations are located, and station verticals are drawn in. Upper and lower ordinates are plotted, trailing-edge and nose *radii* drawn in, and the contours then splined.

Ordinates are given based on a 100-in. chord. For larger or smaller chord length, multiply the ordinate and station figures by the chord length under consideration.

The trailing-edge 100 per cent ordinates are given either as zero or as small percentage values in the basic ordinates. In either case, it is necessary to modify the last three or four ordinates slightly to accommodate a set structural trailing-edge radius which is usually about $\frac{1}{8}$ in.

The contour is altered just sufficiently far forward to give a fair line into the trailing-edge radius. This modification is necessary only on the root and tip sections of the wing, all intermediate sections being developed from these.

Root and Tip Sections.—The wing envelope is defined by a root section, a tip section, and their relative position. Straight lines on the upper and lower surface extending from percentage points on the root section to corresponding points on the tip section complete the envelope.

Thickness Taper.—In order to decrease the structural section with decrease in bending moment, as sections are considered extending progressively outboard, it is desirable to taper the wing in thickness. This is done by using a root section of large maximum thickness (about 20 per cent) and a tip section of small maximum thickness (about 10 per cent) and also by a taper in *plan form* which further reduces the thickness toward the tip.

Plan Forms.—Plan forms are as numerous as a designer's whims. Figure 5 shows representative types.

Aerodynamic considerations as to aspect ratio, structural arrangement, and simplicity of construction govern plan form. For instance, a constant-chord center section permits uniform rib contours and may allow one rib to be used in several places. Sweepback is sometimes used to adjust the m.a.c. with respect to the airplane c.g.

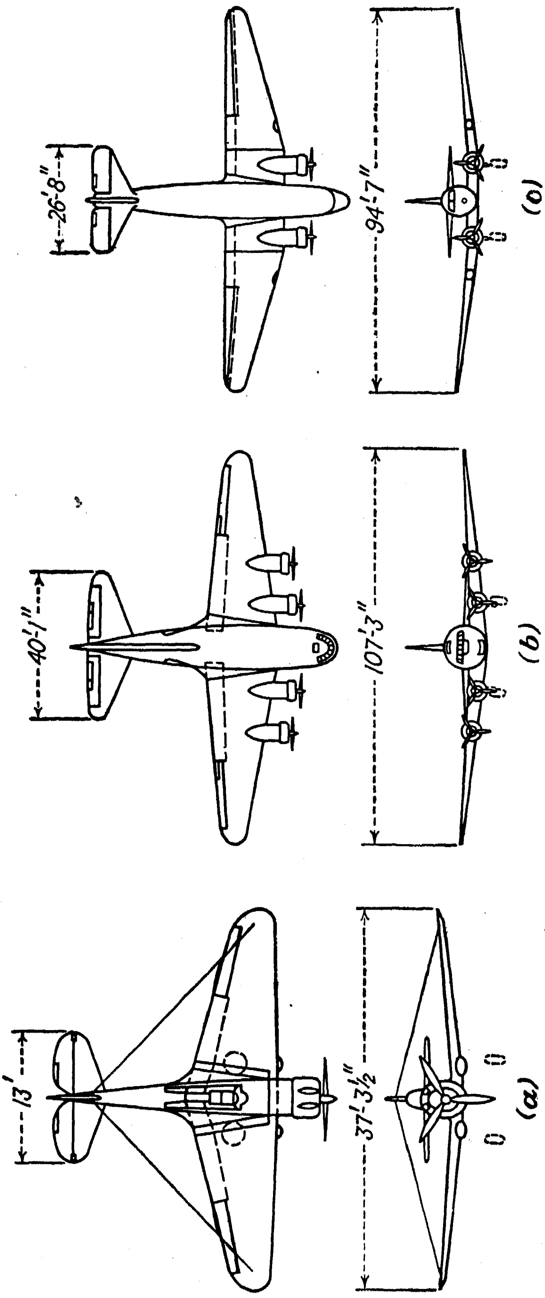


FIG. 5.—Plan forms of airplane wings with different power-plant and empennage arrangements.

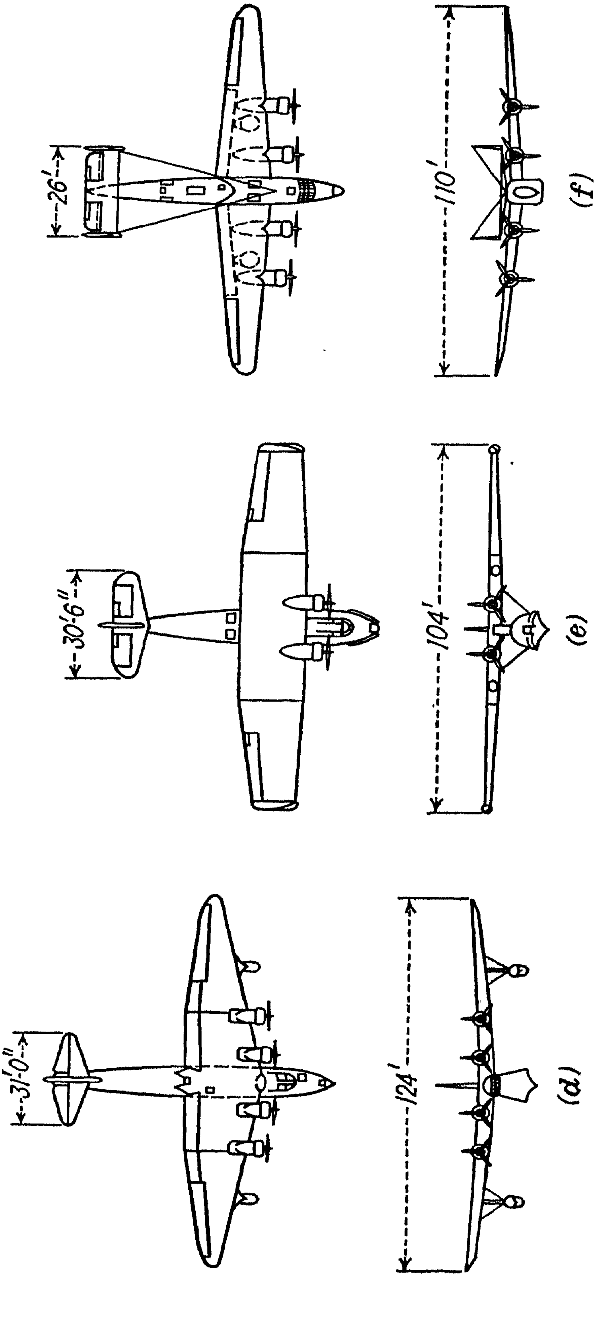


FIG. 5.—(*Continued.*)

Establishing Lines.—The root and tip sections and their relative positions having been established, intermediate wing contours may be determined either graphically or analytically.

There are two principal graphical methods. Figure 6 illustrates the first of these. The root and tip sections are plotted with their chord lines parallel and spaced apart by the semispan to a convenient scale. They are usually staggered with respect to each other in order to obtain sharp intersections of percentage lines. This stagger need not be to scale. Percentage lines are

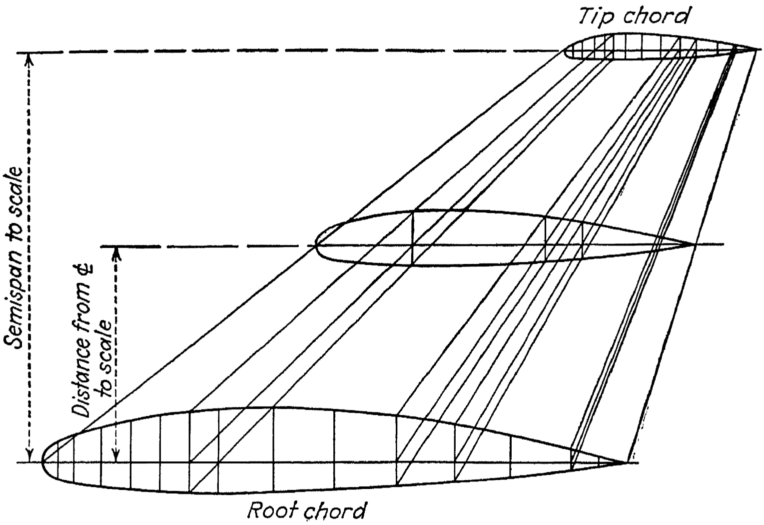


FIG. 6.—Graphical representation of a wing envelope.

drawn, and also lines through station points on the chord lines. To obtain an intermediate section, locate the desired chord line at its semispan location. Draw verticals through intersections of this chord line, and station point rays of root and tip chord lines. Upper and lower ordinates are then the points where these verticals intersect corresponding percentage lines.

The second graphical method is shown in Fig. 7. This method employs a front view of the wing foreshortened in semispan, and a plan view back to the 10 per cent line, also foreshortened in semispan. Intermediate sections are established by locating the section plane in both views and either scaling or tramming the ordinates and station locations.

The analytical method amounts to computing the elements of the second graphical layout.

Slopes of percentage lines with respect to the chord line are computed. These are multiplied by the distance of the desired

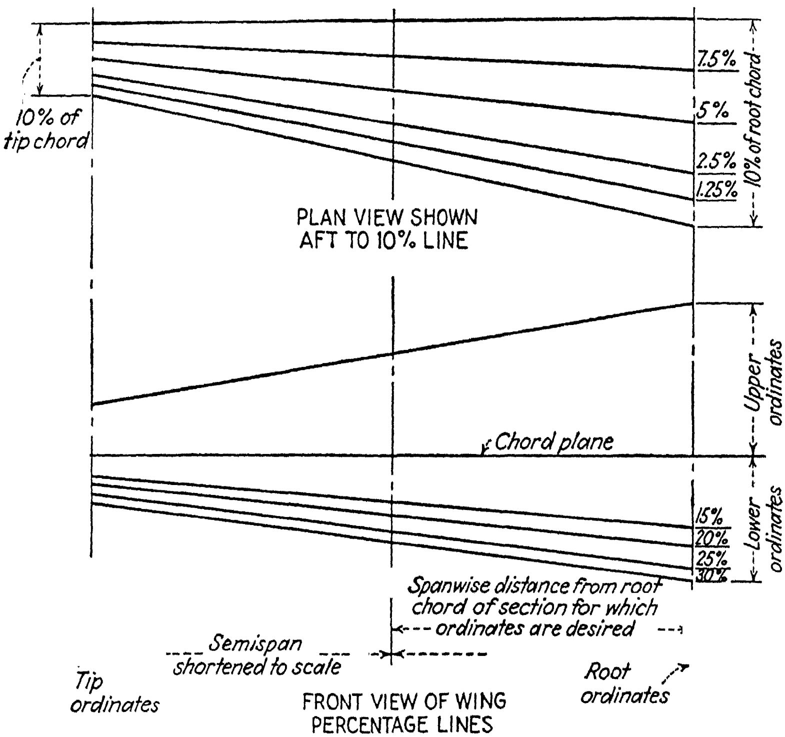


FIG. 7.—Orthogonal projection of wing ordinate lines.

section from the root, and these products are subtracted from respective root ordinates to give the new section ordinates.

$$\frac{\text{Ordinate root} - \text{ordinate tip}}{\text{Semispan}} = \text{slope}$$

$$\text{Ordinate root} - \text{slope} \times \text{distance to section} = \text{new section ordinate}$$

This method is accurate, is easily checked, and has the advantage of eliminating the personal factor in layout accuracy.

Wing-tip Lines.—Wing-tip lines are established by fairing the desired shape to the basic wing envelope. Figure 8 illustrates a method of fairing.

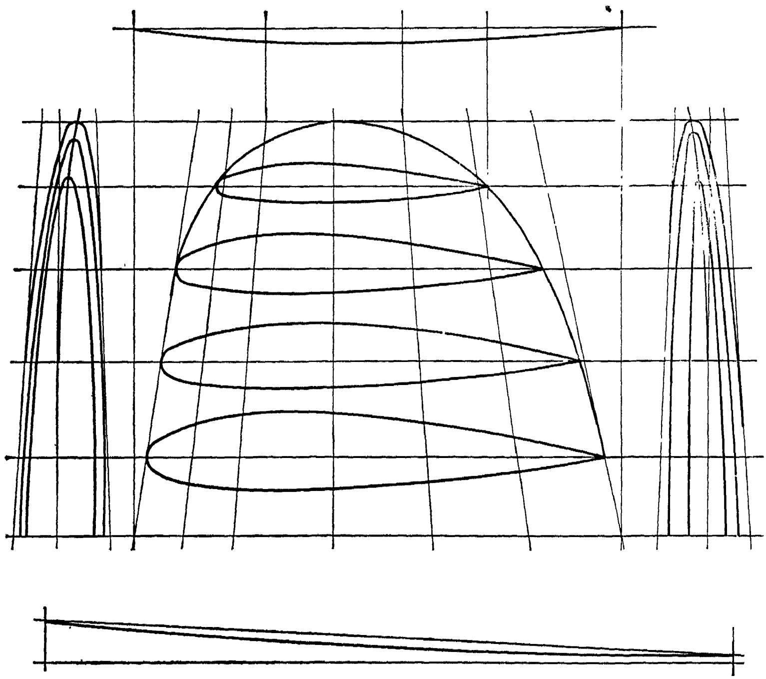


FIG. 8.—Fairing wing-tip lines.

Structural Elements of the Cantilever Wing. *Wing Loads.*—Figure 9 shows three views of a wing with the principal loads applied.

Figure 9 shows the approximate *chordwise* distribution of air loads, better than 60 per cent being applied on the upper surface.

Figure 9 shows the approximate spanwise distribution of air load and the bending-moment curve due to air loads. It explains the necessity for increase in structural section toward the center line of the wing. In addition to bending loads normal to the chord plane, torsion and chordwise bending are induced by the external loads.

Spars, Bulkheads, and Bending Material.—The wing must be able to resist all loads without extreme deflection. It must also

be sufficiently rigid to preclude the possibility of flutter, and light secondary structure must be able to deflect with the wing

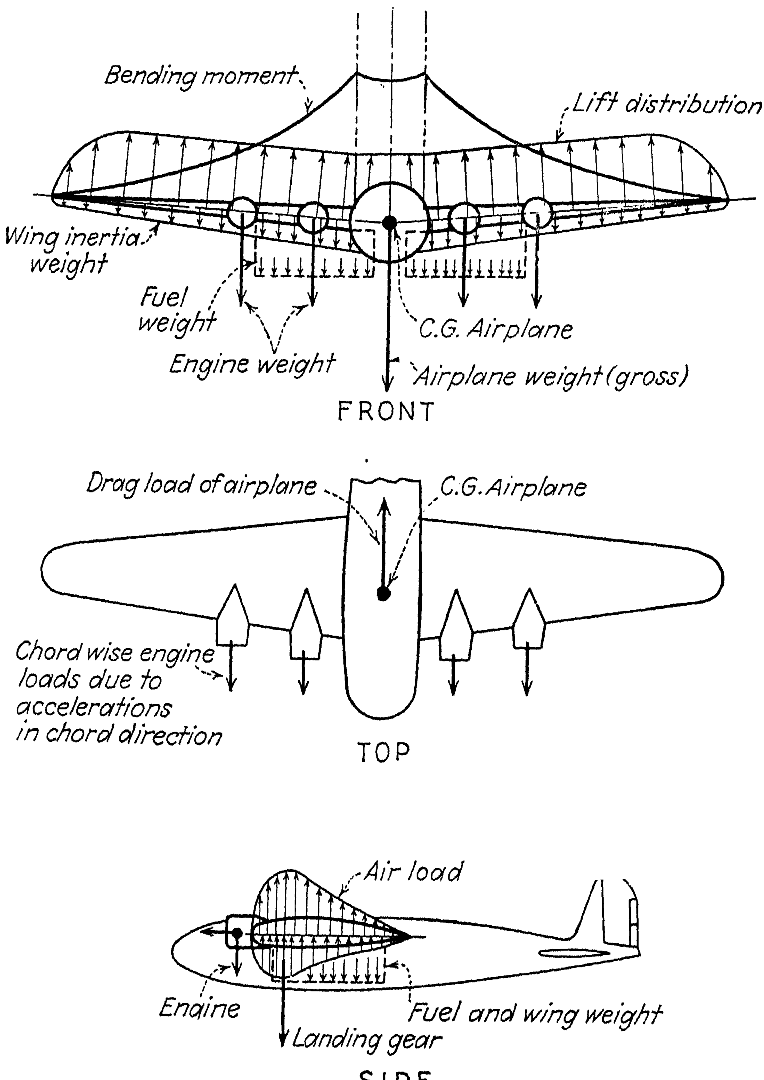


FIG. 9.—Principal loads applied on a cantilever wing.

without damage. The most common type of cantilever metal wing is basically a box beam.

Figure 10 shows the structural layout of such a wing.

The spars form the backbone of the wing and carry shear. Spaced at intervals between the spars are the ribs, or bulkheads, which give the wing its shape and serve to distribute the air and concentrated loads.

Material on the upper and lower surfaces between the spars carries the compression and tension loads due to wing bending.

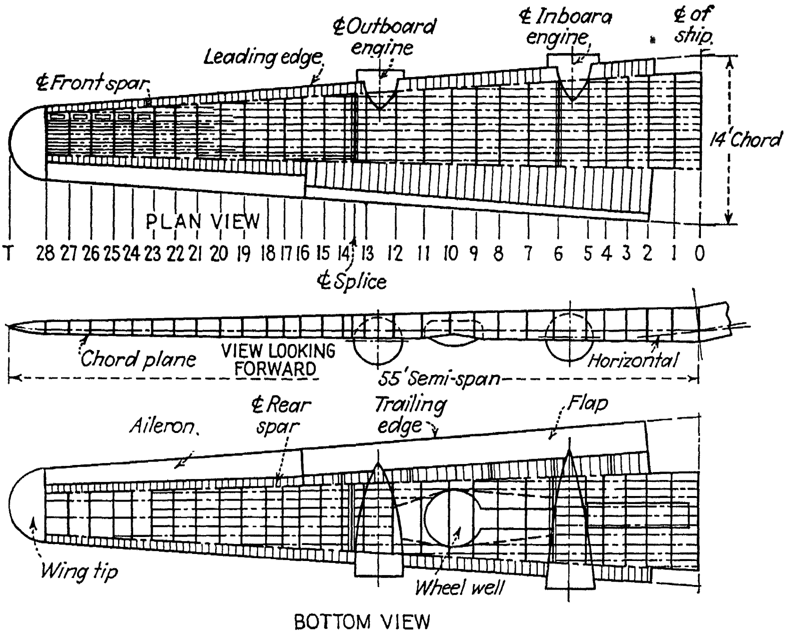


FIG. 10.—Structural layout of typical all-metal cantilever box-spar wing.

This material may either be concentrated at the spars as in the two-spar wing or be distributed as in the case of the stressed-skin box wing.

Leading edges and trailing edges complete the wing structure. These units usually are designed to carry air loads alone; but, in some cases, leading edges carry part of the wing bending.

General Design Considerations. *Spar Location.*—Spars are located to satisfy several conditions. They must have adequate depth for structural strength, and usually they are located on percentage lines so that their contours shall be straight lines. They must be spread sufficiently to allow adequate fuel capacity

if integral fuel tanks are used. Spreading the spars also cuts down leading-edge, trailing-edge, flap-track, and aileron-hinge-bracket loads. Landing-gear-wheel room, float-brace structure, and hull-, or fuselage-, attachment fittings also influence spar location.

Bulkhead Spacing.—In the case of a plate-stringer box-beam wing, bulkheads must be spaced sufficiently close to give adequate column support to stringers. It is desirable to locate them at points where engine fittings, hull-attachment fittings, and flap-track and aileron-hinge brackets attach. Panel-splice and fuel-tank considerations also influence their location. Where fuel cells are used, it is desirable to space bulkheads far apart in order to reduce the number of cells and connections.

Splice Location.—Panel-splice location is usually set to hold the size of the center section and outer panel to convenient sizes for handling in the shop and for shipping. The splice location is usually midway between bulkheads and at a point where it does not interfere with other installations.

Nacelle Location.—Nacelles are located to suit aerodynamic requirements as far as possible and to give proper propeller clearance. It is often necessary to compromise somewhat in respect to their size and position in order to accommodate landing-gear or armanent installations.

Nacelle construction is of three general types.

1. Monocoque. Nacelle shell takes engine-mount loads and at the same time provides nacelle form.

2. Integral oil tank. Oil tank forms part of nacelle structure and provides anchorages for engine mount. Loads are carried into wing by means of side trusses and stressed shells.

3. Frame structure cowled. Engine-mount structure attaches directly to wing fittings. Nacelle shape is maintained by cowling.

Care must be exercised in nacelle attachment to the wing to prevent local failures due to power-plant vibration. Steel bolts used at critical places may save much trouble due to rivet failure.

Fuel Tanks.—Fuel tanks may be integral with the wing or may be separate tanks *cradled* therein.

Considerable weight saving and freedom from complication result when tanks are made integral. The cost of ensuring gas

tightness is slight; for, in most cases, very few rivets need be added for gas tightness beyond those structurally required. Gas-tight bulkheads require special stringer splices or other means for ensuring gas tightness around stringer-bulkhead intersections. There are several simple methods in use, and the weight cost is small. Seams are either lined with neoprene, a synthetic rubber, or smeared with a paste impervious to gasoline.

STRUCTURAL DESIGN—CANTILEVER WING

Types.—There are several types of cantilever wings in general use. These differ primarily in spar arrangement and the disposition of wing-bending structural material.

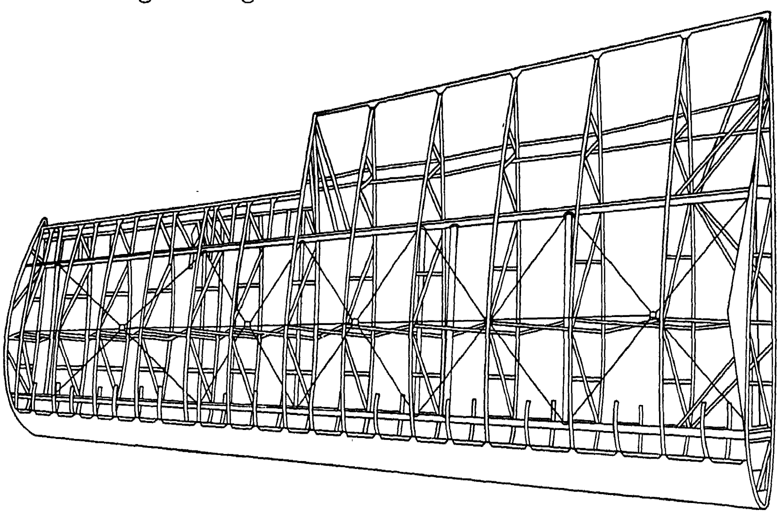


FIG. 11.—Two-spar wing with wire dragbracing, designed for fabric cover.

Figure 11 shows a two-spar wing in which bending is carried by the spar flanges and which uses drag wires because it is fabric-covered. Some two-spar wings use metal skin for carrying drag and torsional loads.

Figure 12 shows the construction of a conventional two-spar box-beam wing, a D tube, and a narrow box-beam wing.

Multispar wings employ three or more spars and use them, together with subbulkheads, to maintain the wing shape.

Structural Sections.—Figure 13 shows a number of aluminum-alloy extruded sections which are used as structural elements in wing construction.

Figure 14 shows similar sections that are drawn from sheet stock. The z and hat sections are used in plate-*stiffener* com-

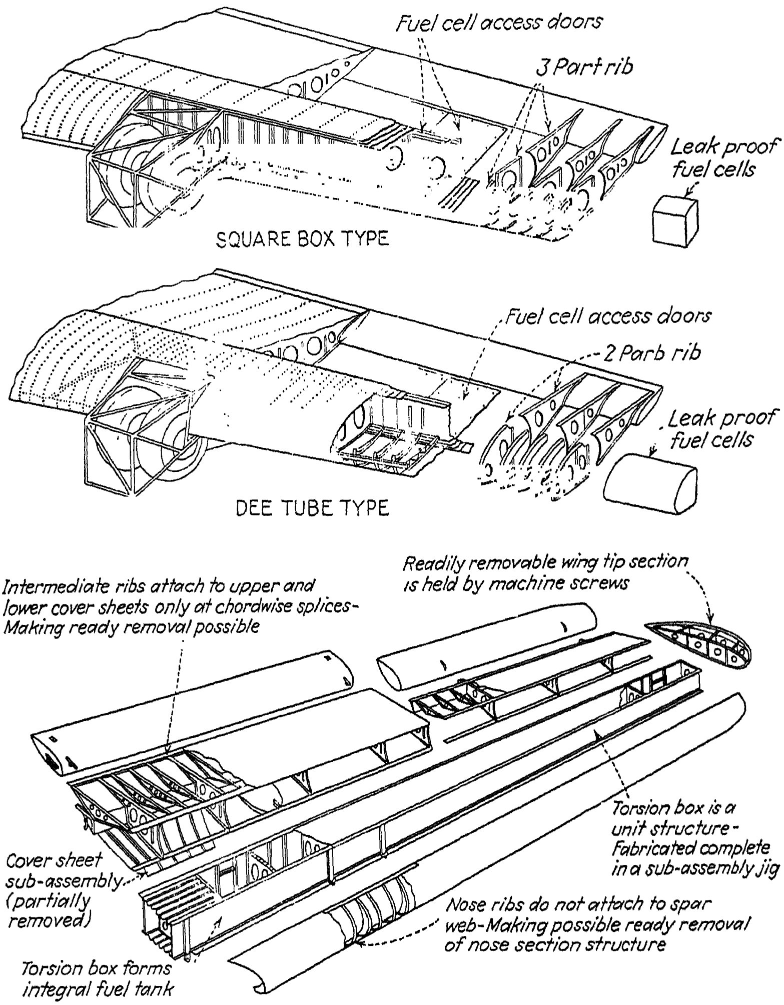


FIG. 12.—Three types of cantilever box-beam stressed-skin wings.

binations. Angles are used as stiffeners and for ties. Extrusions are more accurate and uniform than drawn sections and are able to take greater loads normal to the heel of the angle without *setting*. They are available in a great variety of shapes. Drawn

sections likewise have the advantage of ready *availability*, because they are made from sheet stock. Also, they may be had in *Alclad* which is an asset where corrosion is an important factor.

Figure 15 pictures a number of small forgings used in wing construction. Figure 16 shows large forged hull attachments

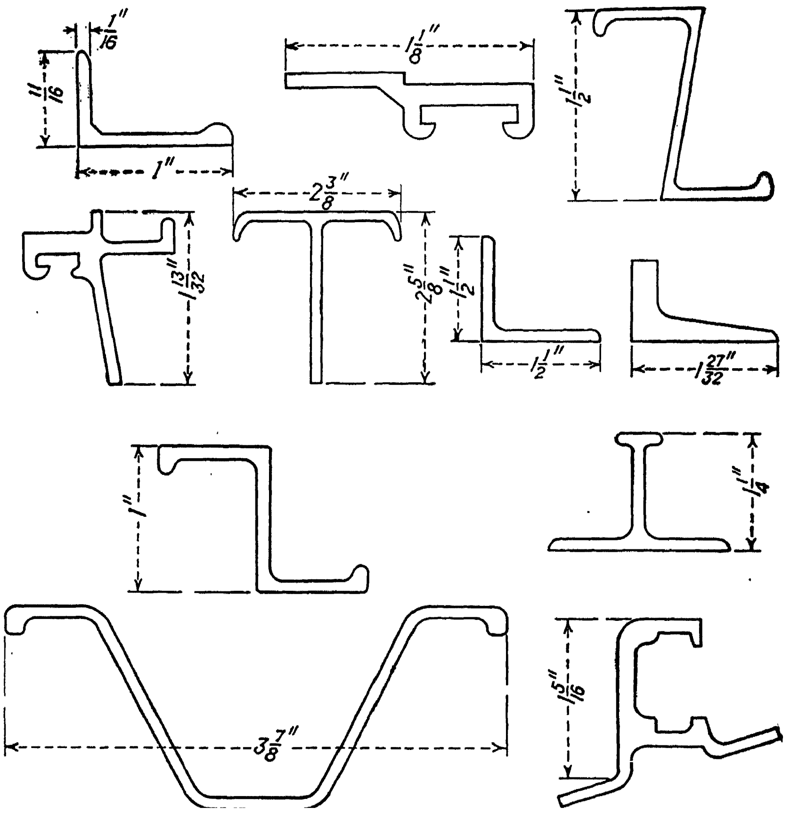


FIG. 13.—Typical extruded structural shapes used in wing construction.

and hoist fittings. Forgings are used for highly stressed fittings. The use of castings is restricted to lightly stressed parts, usually in secondary structures.

The Two-spar Plate-stringer Wing.—Figure 10 shows the structural layout of a two-spar plate-stringer wing.

There are two methods of setting bulkheads and ribs. The wing shown has bulkheads set normal to the chord plane. The other method is to set them normal to the ground line.

Figure 17 shows several types of *spar construction.* Figure 17-*a* shows a shear web with extruded angle flanges and joggled stiffeners. Figure 17-*b* shows a spar with single flange extrusion and straight stiffeners. Figure 17-*c* shows a spar with drawn-section flanges. The Wagner-beam spar gives a light efficient structure with easily fabricated component parts. Stiffeners may be plain or bulb angles or z or t sections. Bulkhead attach-

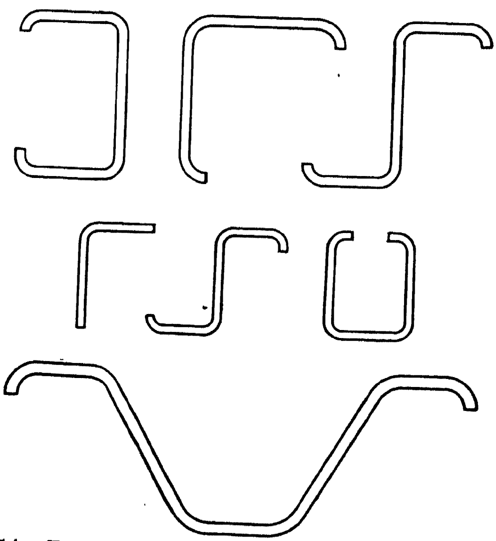


FIG. 14.—Typical drawn sections used in wing construction.

ment may be made directly to the outstanding leg of a vertical angle.

Where reinforcing sheets are added under the wing skins, the spars are joggled to accommodate their thickness. Web splices are easily made by joggling one sheet over the other to give an overlap large enough to take the required number of splice rivets. Spar flanges are spliced by *nesting* an angle similar to the spar flange through the region of the splice.

In the gas-tight region of the *wing,* a *neoprene* strip is inserted between the spar flanges and the web. *Rivet* spacing through the flanges in this region is held to $3\frac{1}{2}$ diameters.

Small holes cut in the web can be easily reinforced with patch plates. Large openings such as those required for ducts can be

taken care of by means of an adequate diagonal from *station* to *station* each side of the opening.

The function of *bulkheads and ribs* has already been described. In regard to type of construction they are of three general kinds, trusses, Wagner beams, and pressed sheet.

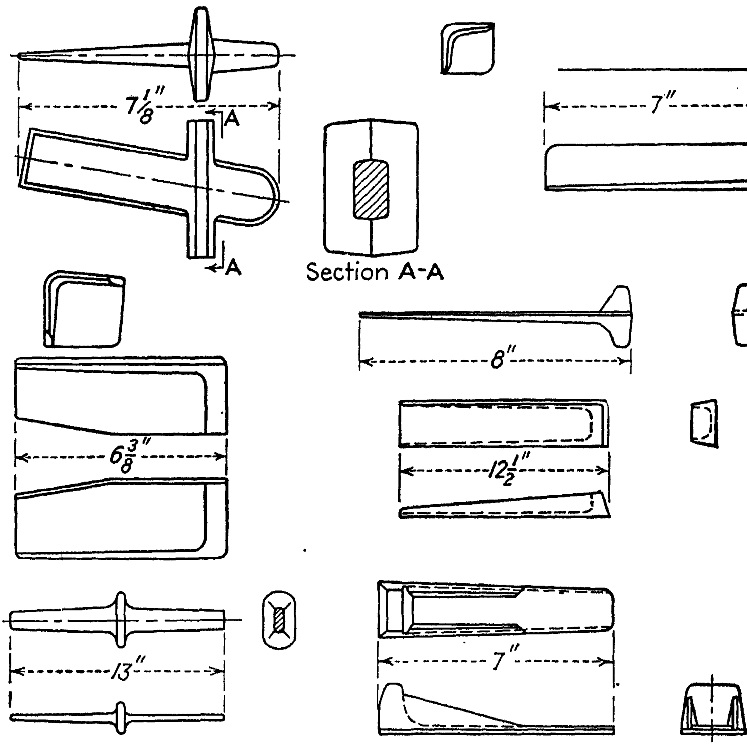


FIG. 15.—Small aluminum-alloy forgings used in wing construction.

Truss bulkheads are usually of the Warren type, with panel points located so as to hold down chord-member bays and the column length of diagonals.

Chord members may be bulb angles, *z* sections, channels, hats, and diagonals likewise. A simple truss rib using drawn-channel diagonals and drawn *z* chord members is shown in Fig. 18. By using pressed-sheet-channel chord members in place of the *z* sections a still simpler structure results.

A truss rib suited for high loadings employs hat-section chord members and drawn-channel diagonals. Gussets are used to

tie diagonals and chord members. Some small ships use simple trusses built up of spot-welded stainless-steel channels, gauges as light as 0.006 being used. Truss bulkheads are attached to spars by means of gussets which rivet to the outstanding leg of vertical angles on the spars.

Wagner-beam bulkheads form light efficient structures but require the use of minimum web gauges. These are subject to

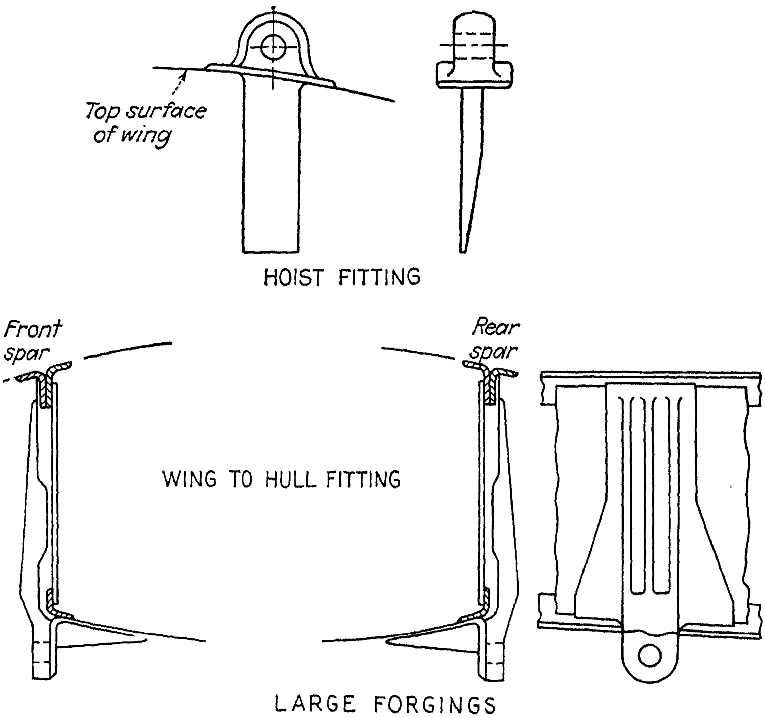


FIG. 16.—Large aluminum-alloy forgings used in wing construction.

"oil cans" on larger bulkheads, and they also require considerable riveting.

Gas-tight bulkheads are of the Wagner-beam type. They are built up substantially in the same fashion as the Wagner spar. These bulkheads are usually built to wing contour, and stringers are spliced through by means of bolted forgings or a flanged bar called a *dagger fitting*. In most setups the stringer splice fitting is not on the centroid of the stringer, and a splice plate is also required over the bulkhead. This does not work

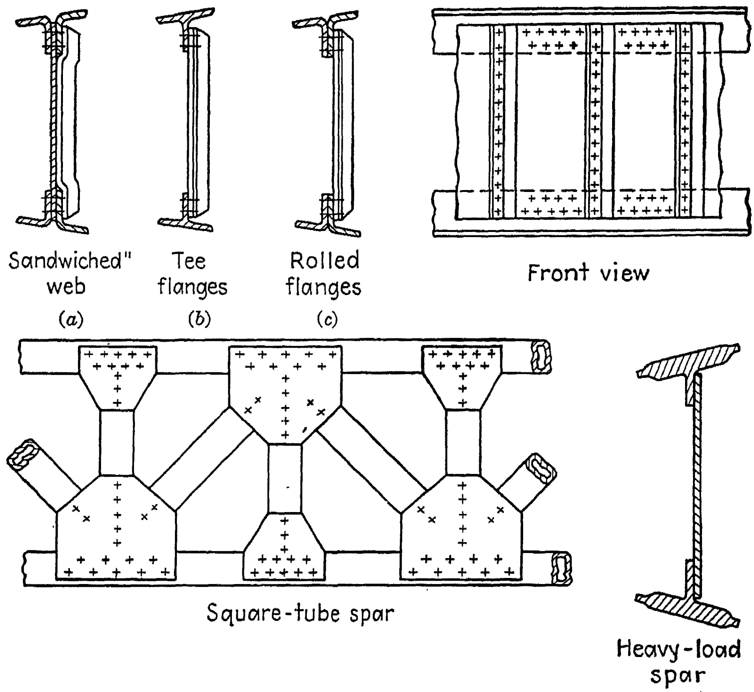


Fig. 17.—Typical spar construction for stressed-skin wings.

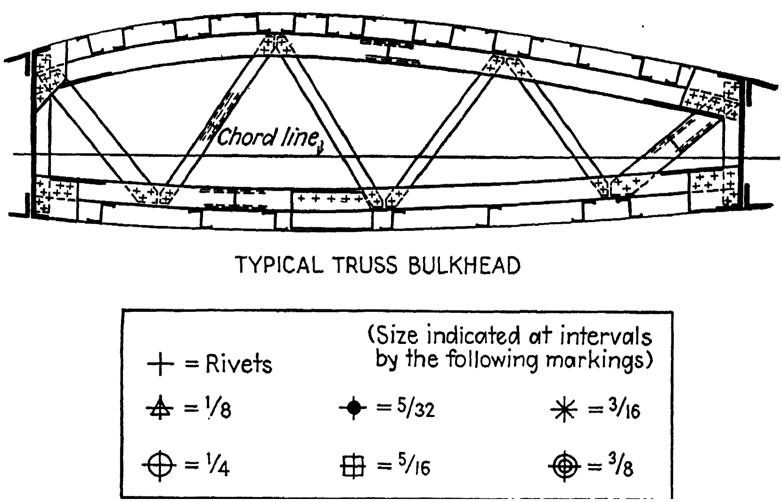


Fig. 18.—Simple built-up truss bulkhead for stressed-skin wing.

a hardship, for skins can be conveniently spliced at the bulkhead and the splice plate heavied to suit. Since fuel tanks are air-tested to 3 lb. per sq. in., the bulkhead stiffeners are frequently designed by this test loading.

One of the isometric sketches shows a gas-tight bulkhead using dagger fittings. A pressed-sheet bulkhead is shown in Fig. 12; it is by far the simplest form of construction. Pressed parts cannot as yet be completely analyzed to permit construction without confirming tests, but this type of construction is used wherever possible on new designs. Limitations such as access room at a wing splice or perhaps inability to meet weight allowances may call for another design.

The main working parts of the wing are the *plate-stiffener combinations*. The upper surface must be capable of carrying compressive stresses as high as 40,000 lb. per sq. in.

In order to make the wing skin work to high compressive stresses, it is backed up either by z or by hat sections. These are spaced closely to eliminate *free* sheet of any considerable size. The spacings and the allowable stresses such a section will carry are determined by running a series of tests for different stiffener spacings and gauges, and at the same time simulating actual wing-column lengths.

On large ships, stringers are $1\frac{1}{2}$ to $2\frac{1}{2}$ in. deep. For $1\frac{1}{2}$ z or hat sections, a bulkhead spacing of 24 to 36 in. is usual. For the $2\frac{1}{2}$-in. hat sections, this may go as high as 48 in.

Stiffeners on the lower surface are usually open sections, particularly where they are used in integral fuel tanks. Hat sections, being closed, do not permit inspection or cleaning.

The lower surface of all wings seems to be dedicated to landing gears, bomb bays, gun installations, fuel cell access doors, float braces, etc. Usually the upper surface is kept relatively clear and is a straightforward job. Most wings manage to achieve at least a region where the cross section is a C channel, with various slugs at the lower flanges of front and rear spars.

In the outer panels where the loads have considerably dropped off, stringers are spliced to smaller sections. It is also usual to splice down to thinner skin gauges holding the same depth of stringer.

Skin splices spanwise can be made in three ways, (1) by using an internal *butt strap*, (2) by using a buried splice plate, and (3) by joggling one of the plates.

Rivets on the larger wings through skin and stringer run $\frac{3}{16}$ spaced at 1 in. and they are countersunk on the upper surface from the leading edge back to an arbitrary percentage line or to the rear spar. Rivets on the lower surfaces $\frac{3}{16}$ or under are usually brazier head.

One of the most interesting and most important wing-design problems is the *outer-panel-to-center-section splice.* Such splices must now be internal for aerodynamic cleanness. This splice is usually an internal flush splice, using heavy extruded angles to splice the skin and forgings to splice the stringers.

As wing loads go up, bolt sizes increase and the distance of bolt centers from the skin increases. Finally a point is reached at which this type of splice is barely adequate in tension on the lower surface. The upper surface is satisfactory because the skin loads are transmitted by bearing directly across the heels of the extruded angles.

Another complication in recent designs of splices is that the joints must sometimes be gas tight in addition to meeting strength requirements. A special blind elastic stop-nut solves the problem of gas tightness. Another form of this splice could be made with buried skin-splice angles.

Interchangeability is one of the main requirements of a wing splice. This makes the splice-plate type difficult. Also the structural strength of such a splice is not enhanced, owing to the difficulty of getting all skin bolts to work uniformly.

The spar webs are usually spliced with butted extruded angles bolted together, shear plates being used for the reasons mentioned above. Spar flange angles are spliced with angles and forgings and large bolts.

Attachment of the wing to the hull or fuselage can be accomplished in a number of ways. On the *boats*, four large *fittings* are riveted to the spars so as to provide large male lugs which rest in mating fittings on the hull. They carry pins set in a fore-and-aft direction. The wing is also tied in to the hull skin by an angle riveted to the lower surface of the wing. This tie carries drag loads; vertical loads are, of course, carried in the main lug fittings.

Design for Special Conditions.—*Retractable float installations* used to date are of two types. The PBY type (Fig. 19) retracts to the wing tip and requires a large tip section. Cutouts are

required in the end of the outer panel for the drag brace, the links, and the actuating screw and trough. Hinge fittings must also be provided. Fortunately, loads other than those brought in by the float structure are light; it is a case of minimum sizes practically throughout.

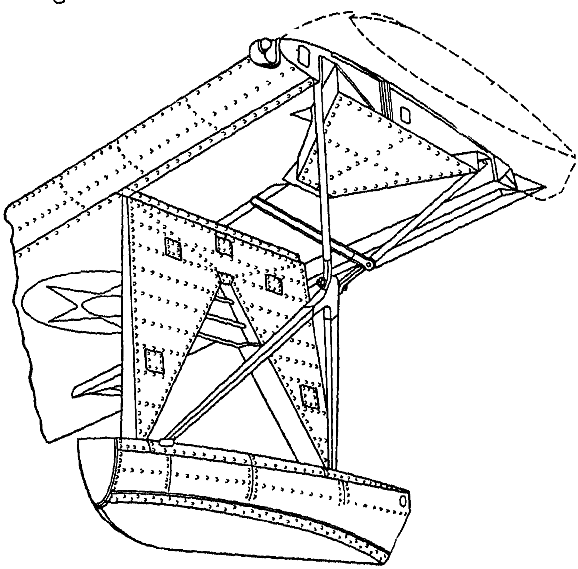


FIG. 19.—PBY-type retractable wing-tip float.

The second type of float installation brings the float up to the lower surface of the wing and completely retracts the float-brace structure. This is a somewhat more difficult structural problem because it occurs in a higher stressed region of the wing. The float brace and retracting mechanism operate between two auxiliary spars approximately 10 ft. long. At the outboard end of these spars is a heavy bulkhead to which are anchored the main drag-strut fittings. The wing in this region amounts to two boxes connected by a skin on the upper surface.

Bomb provisions may be internal or external. Stowing eight bombs approximately 85 by 19 in. diameter in the center section is another case where refinements of design must be sacrificed to considerations of space.

Landing-gear wheels may be retracted laterally into the lower surface or back and up into the nacelle between the center-section spars. The latter method is preferable, but space limi-

tations may prevent its use. This method cuts out very little wing material and keeps the landing-gear special conditions concentrated.

Fuel cells are still in the process of development. They affect the wing in that *doors* for installation must be provided and surfaces contacting the cells must be smooth. As mentioned before, bulkhead spacings may also be altered to accommodate cells.

One very important consideration, particularly on flying boats, is the *prevention of corrosion.* Some of the points to be watched are as follows:

1. Eliminate use of dissimilar metals. Steel bolts are undesirable for this reason.
2. Eliminate pockets or voids that will retain moisture.
3. Use zinc chromate paste or other filler in cracks and seams exposed to salt water.
4. Provide drainage and adequate inspection holes.
5. Use potassium dichromate containers in integral fuel tanks.
6. Eliminate closed sections.
7. Use Alclad sheet instead of dural.
8. Anodize and prime material.
9. Avoid the use of canvas webbing or other material that retains moisture.

Integral Fuel Tanks.—Some points in connection with integral fuel tanks have already been mentioned. Gas tightness is achieved by drop-hammered suitcase corners that are carefully riveted to the structure after having been treated with neoprene. Slots are left for packing with plugging. Gas tightness was achieved on older ships with neoprene exclusively. Lately, zinc chromate paste has displaced neoprene for many conditions. However, it has the disadvantage of being extremely dirty and of picking up chips. Also, it makes the efficacy of the job the responsibility of the workman. A combination of neoprene and paste, each used where it is the most effective, seems to be the answer.

Leading Edges.—Leading edges may be designed to carry air loads alone, or they may contribute toward wing bending by furnishing some flange material.

A simple arrangement is shown in Fig. 20 where pressed nose ribs of channel section are spaced approximately 12 in. apart

and two plain angle former sections are used between ribs. Ribs and formers are riveted to 0.025 skin and both riveted to an edging extrusion which carries a single line of screw holes for attachment to the spars. This arrangement divorces the leading edge from the spars and also gives ample room for installations.

As the wing deflects the free leading edge, the skin between the ribs and formers buckles slightly. Up to 2 g's this buckling is scarcely apparent.

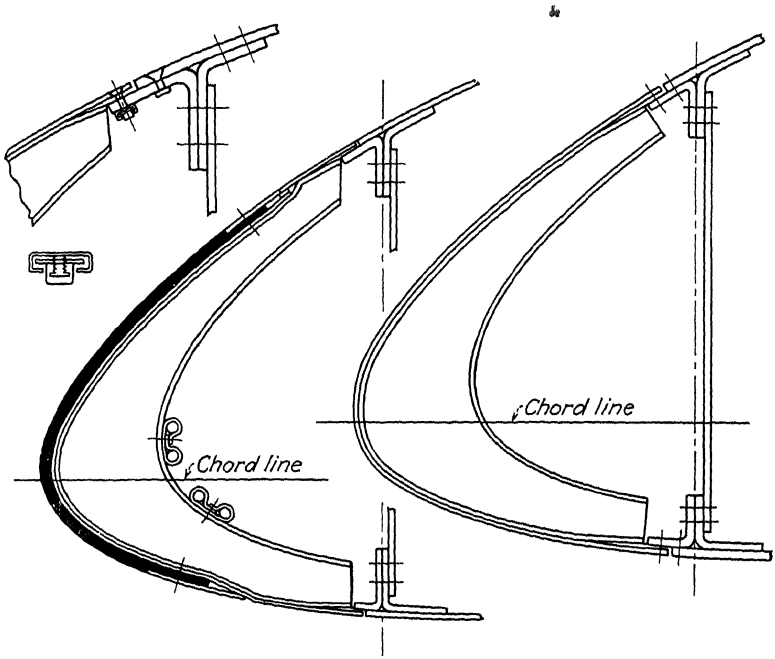


FIG. 20.—Pressed leading-edge ribs, with and without provision for de-icer boot.

De-icers are laid over this leading edge and attached to Rivnuts on the upper and lower surfaces. In order to smooth out some of the de-icer build-up, latest leading edges are recessed to accommodate the de-icer. Even so this installation is still not very smooth.

Wing Tips.—Wing tips are made detachable to permit ready replacement in the event of damage. A typical wing tip consists of two channel spars to carry shear ribs, a tip bow to maintain contour and stiffened skin to carry bending. It is very likely

that plastic-impregnated plywood molded under pressure and heat will offer a cheaper solution to the wing-tip problem.

DRAWING PROCEDURE

Layouts, Studies, and Shop Drawings.—The wing group's first opportunity at a new design comes when a three-view drawing and proposal data are turned over from the preliminary-design group. The first step is to work up a structural layout, already shown, determining spar locations, bulkhead and fitting locations, and other debatable points. From now on, considerable time is spent in preliminary layouts and in coordinating the wing to suit the requirements of other groups before shop drawings can be started. During this period the structures group work up data which enable them to give member sizes when needed.

Spars, bulkheads, forgings, and other parts requiring considerable time to build are first drawn up and released. Other parts are released in correct sequence so as to ensure their availability when needed at assembly.

Wing drawings are usually split up into the following major assemblies:

- Wing installation
- Center-section assembly
  - Center-section lower-surface plating
  - Center-section front spar
  - Center-section rear spar
  - Center-section bulkheads and ribs
  - Landing-gear fitting installation
  - Engine fitting or nacelle installation
  - Center-section—outer-panel splice installation
  - Leading-edge assembly
  - Trailing-edge assembly
  - Controls installation
  - Flap assembly
- Outer-panel assembly
  - Outer-panel lower-surface plating
  - Outer-panel front spar
  - Outer-panel rear spar
  - Outer-panel ribs
  - Outer-panel leading-edge assembly
  - Outer-panel trailing-edge assembly
  - Wing-tip assembly
  - Aileron assembly

About 450 shop drawings are required to define the wing structure in the case of an experimental airplane. Drawings for production airplanes are more detailed; up to 1,000 drawings may be required for these.

Common Drafting Errors.—Engineering drafting and layout practice require skill that can be obtained only through experience. A thorough grounding in engineering fundamentals is essential, but one learns best by doing and finding his own mistakes occasionally.

The success of any design is dependent on the workability of its smallest details from the standpoint of construction in the shop. How well the unit fulfills the requirements for which it is designed is only part of the story—getting it built comes first. Attention to seemingly trivial detail is essential. Parts must be accurate, must allow for shop variations, and must permit easy fastening.

Following are a few items that frequently give trouble:

1. Failure to allow room for rivets. Insufficient edge distance; insufficient center-to-center distance. Interference with adjacent part or fillets; insufficient room to form the head; inability to drill hole or enter the rivet. Rivets inaccessible for driving or bucking.

2. Failure to allow for shop variations. Brackets contained between variable surfaces. Insufficient edge distance for fastenings, due to failure to provide flange bend allowance. Insufficient machining allowance on forgings and castings. Working to small clearances.

3. Bill-of-material and clerical errors. These nuisance errors frequently result in considerable time loss and scrappage. They are largely the result of carelessness.

4. Unnecessary drafting. Give sufficient information to make the part and no more. Showing bolt and rivet heads, excessive hatching, and ultrafancy printing contribute little or nothing to the drawing.

5. Unnecessary degree of accuracy. Where a high degree of accuracy is not required, time is lost and nothing is gained.

6. Interferences—putting two things in the same place.

7. Failure to follow through completely when changes are made. Changes are always more far-reaching than they appear. Careful study will help to get the whole story.

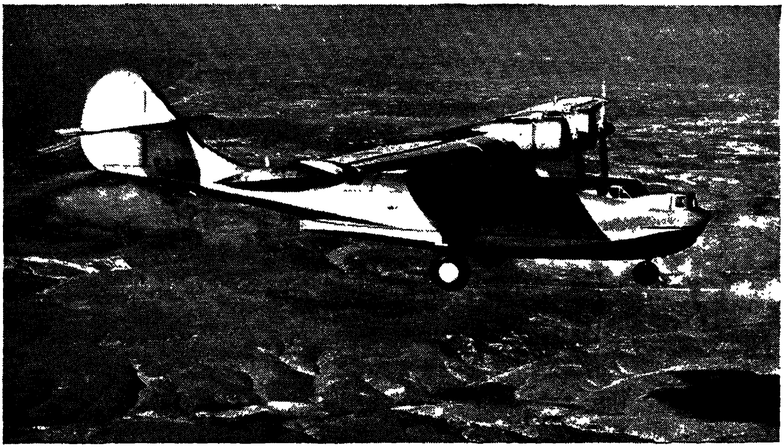
8. Failure to check with the shop on questionable practices such as difficult forming or joggling.

9. Failure to go over the drawing from the standpoint of the shop in regard to completeness of information. The shop will get the drawing, not the draftsman's notes and thoughts.

10. Failure to give largest tolerance consistent with the design. The shop cannot tell which dimensions are important unless these are indicated on the drawing.

11. Failure to give assembly procedure, notes, and warnings. Many jobs go wrong in the shop because of failure to acquaint the shop with the method of assembly intended.

12. Dimensioning to theoretical points that are difficult for the shop to establish.


Consolidated amphibian flying boat prepared for airfield landing. (*Official Photograph, U.S. Navy.*)

CHAPTER V

FIXED EQUIPMENT

In the previous chapters it has been shown how the airplane is divided into several components, each component being designed by the various design groups that comprise the engineering department. One of these design groups is the fixed-equipment group. The name seems to imply that all that is permanently installed in an airplane is fixed equipment. However, that is not so. Engine controls, for instance, which are permanently installed in the pilot's compartment, are part of the responsibility of the power-plant design group; the tables and shelves for the radio operator, although they are fixed equipment, are handled by the electrical design group.

Responsibilities of the Group.—Under the heading of fixed equipment are the following items:

1. Furnishings
    - Armament provisions
    - Radio
    - Hydraulics
    - Tables
    - Seats

Comfort provisions
Navigator's provisions
Miscellaneous lockers
Miscellaneous equipment
Emergency provisions

2. Handling gear
   Anchor installation
   Sea anchor installation
   Hoisting gear
   Mooring gear
3. Electrical equipment (to be discussed in Chap. VIII)
4. Hydraulic equipment (to be discussed in Chap. IX)
5. Controls—control mechanism in cockpit and surfaces, excluding engine controls, cable brackets, and routing
6. Fire extinguishers
7. De-icer and anti-icer installation (anti-icer done by power-plant group)
8. Heating, ventilating, soundproofing
9. Instrument lines and panel installations

In this chapter, the larger airplanes and a particular group system only will be discussed. To clarify what the fixed-equipment group handles and what their problems are, a more detailed enumeration follows.

The fixed-equipment group is itself divided into groups. Each group, headed by a leadman, is responsible for one particular model; "model" means all airplanes that originate from the same prototype airplane. Each of these groups, then, is responsible for the design of the following items for the particular model:

1. Controls, *i.e.*, all the control elements in the pilot's cockpit and throughout the fuselage, or hull, up to the control surfaces.

2. Instrument and instrument-panel installation. De-icer and fire-extinguisher installation and installation and hookup of all piping except fuel- and oil-system piping.

3. Heating, ventilation, soundproofing, and comfort (bunk installations, galley installation, lavatory installation, personal lockers, etc.).

4. Handling gear, *i.e.*, hoisting slings or shackles, anchor and towing provisions, oxygen installation, navigation provisions, and miscellaneous equipment. The last item, in general, consists of all seats except the special seats used for the bomber or the gunners, the latter being taken care of by the armament group. Miscellaneous lockers, workstands, and ladders. Emergency provisions, such as parachutes, life jackets, first-aid kit, and stowage of emergency food rations and water.

5. Furnishings and fixed-equipment drawings showing all the various items of furnishings and fixed equipment that go into the airplane.

Preliminary Drawings.—One of the first things that is done in starting an airplane design is making the general-arrangement and inboard-profile drawings. Although the general-arrangement drawing, or, as it is often called, three-view drawing, and the inboard profile are not actually made by the fixed-equipment group, they are intimately tied in with fixed equipment. A short description of these drawings will therefore be given.

When the general-design and aerodynamic group have determined the general size of the airplane and considered the minimum room for equipment, they make a general-arrangement, or three-view, drawing. This drawing shows the general outline of the airplane, and gives such details as the span of the wing and the tail, the over-all length, the height, and the ground clearance. In table form are usually noted the general specifications such as gross weight, useful load, weight empty, areas of wings and control surfaces, size of engine or engines in horsepower, maximum and landing speed of the airplane, absolute ceiling and service ceiling, and rate of climb (so many feet per minute at sea level).

Concurrently with the general-arrangement, or three-view, drawing, the inboard-profile drawing is made. This drawing shows all interior equipment of the airplane, such as power plant, fixed equipment, and armament. Usually the inboard profile shows the airplane in side view, plan view, and, for larger airplanes and particularly where there is more than one deck, vertical sections through the airplane or separate plan views for the different decks. The scale of the inboard profile is 1:10 for the U.S. Army Air Forces or 1:12 for the U.S. Navy Department, Bureau of Aeronautics, or either for commercial airplanes depending on the customer's requirements.

Arrangement.—In arranging equipment in an airplane, two things have to be kept in mind.

1. Purpose for which the airplane is being built, such as airline service, bombing, or patrol.

2. Balance of the airplane; *i.e.*, for level flight the c.g. will have to be approximately on the vertical line through the c.p. of the airfoil.

Mock-up.—Before going any further with the design of the airplane, a so-called *mock-up* is made. The purpose of the

mock-up is to check the actual installations. Although layouts can be made for the various installations, there is nothing that can replace actually seeing the various items in operation and the room available at each location. It would be costly, for instance, not only in money but also in time, to find that there was not enough room for all the items or that one item had been allotted to the same spot as another and extensive changes had to be made on the actual finished airplane.

During the progress of the design, frequently desirable changes are made; the mock-up should then be corrected accordingly to prevent any interferences. Even with these precautions, it sometimes happens that a given space has been utilized for two different installations. Usually these interferences are not very serious. However, the importance of a correct mock-up cannot be overemphasized; it saves time in the end.

Pilot's Compartment.—The pilot's compartment will now be described in detail. With the present-day long-range airplanes (30 to 40 hr.), special care has to be taken for efficient arrangement and comfort. Usually pilot and co-pilot are located side by side, the pilot's place being on the left-hand side. The seats are located for easy and comfortable reach to the various control elements and for maximum visibility.

In airplanes capable of long flight, the comfort of the pilot is more than just a matter of nicety of design. A strained and fatigued pilot is not so observant or so quick to respond in emergencies as is one who has been able to relax throughout the flight. One of the most important factors in pilot fatigue is the relative position of the pedals, the control wheel, and the seat. There are certain relationships specified by the armed services that are based on the pilot's comfort and convenience.

To maintain that standard as closely as possible for various-sized pilots, adjustments are incorporated in both the pilots' seats and the rudder pedals. The relative location of seats, pedals, and control column and the adjustments of seats and pedals are normally as follows.

The distance from the intersection of the back and the seat to the pedals is 35 to 41 in. and the distance between the seat and the control column in the extreme aft position is 12 to 14 in. Location of engine controls is x in. ahead of the seat and x in. above the seat. The pilot's seat has ± 3 in. adjustment vertically

and fore and aft. The pedal adjustment required by the U.S. Navy is ± 3 in., and that required by the U.S. Army is ± 2 in. Brake pedals, which are used for landplanes, usually have an adjustment of ± 1 in. For additional comfort, the pilots' seats incorporate tiltable backs for relaxation when a pilot is not flying the airplane or when the airplane is flown by the automatic pilot.

The engine controls are located on a pedestal between the pilots. This same pedestal is also designed for mounting of tab controls, ignition and other switches, control handles for retracting the landing gear, flap-control handles for the extension or retraction of the flaps, and, when possible, pilot's radio control panels.

The instrument panel is located to clear the control column in the extreme forward position. The instrument panel is combined with the controlling elements of the automatic pilot, hydraulic or electrical. Later on, the arrangement of instruments will be discussed in greater detail. Oxygen and interphone outlets have to be located so that the feeder line for oxygen or the cord for the interphone does not tangle up with the control elements or hinder the free movements of the pilots. A location to the side of the crew member approximately opposite the shoulder is a good one. The lines could then come up to the headgear under the pilot's arm.

The pilot also must have access to maps, airplane data sheets, and paper for notes he may want to make. Therefore, there has to be a map or data case within possible reach without leaving the seat. The pilot's map case can, for instance, be located under the seat bucket and the data case to the side a little above floor level.

In the modern airplane, speed is of paramount importance. One of the requisites in meeting speed requirements is to reduce the body of the airplane to a minimum. As a consequence the co-pilot may also be made to serve as an engineer. This means that, in addition to the minimum number of flight instruments, the co-pilot should also have within easy reach the power-plant instruments, all the power-plant controls for starting and trim of the engines, and other auxiliary controls, such as the control of the engine fire extinguisher. One location may be in the floor aft of the pedestal; another location might be on the right-hand side of the seat in the floor next to the fuselage, or hull, side.

Flight Deck.—In addition to the pilots, there are other crew members who form a part of the flight crew. These crew members are the navigator, radio operator, and engineer. When possible, all these crew members, *i.e.*, two pilots, engineer, navigator, and radio operator, should be located in close proximity in the same compartment, usually called the *flight deck.* The flight deck thus includes the pilot's compartment. In PBY-type airplanes, all flight-crew members are stationed, but, they are separated. Thus, there are a pilot's compartment, a navigator's compartment, a radio operator's compartment, and a separate engineer's station. The latter is located in the superstructure between wing and hull. In the later models, however, there is a flight deck; when the size of the airplane and the magnitude and importance of the mission warrant it, a *commanding officer's* station is added. The duties of the commanding officer are coordination of the other crew members' tasks and a general check of their work. As the name implies, he is the captain of the airplane. The location of the "C.O.," as he is usually called, should be as closely as possible centered between the flight-crew stations.

The *navigator,* when at all possible, should be located directly aft of the pilot. His function is obvious. Because he is charged with the navigation of the airplane, he is constantly checking its location and is in more or less constant communication with the pilot. However, that could be maintained over the interphone if it were found impossible to locate the navigator next to the pilot.

The navigator must have good vision and provisions for his maps, books, and instruments. Good vision, of course, is of paramount importance. The ideal condition would be to have 360-deg. vision around all three axes, *i.e.*, vertical, fore and aft, and lateral, an impossibility in any airplane, from one station. However, this may be accomplished by making provisions at several stations throughout the airplane. This arrangement, of course, is quite inconvenient to the navigator, although it is sometimes made. For instance, a bottom gun emplacement, also called a "tunnel" gun, may be used by the navigator for measuring drift of the airplane. If the navigator's requirements are considered when the design is begun, a very workable arrangement is possible. By making the windows reasonably

large, say 10 by 14 in., on the flight deck, installing at least one on each side in a position that it is possible for the navigator to reach, and using the rear section of the pilot's enclosure on either side plus a window in the top of the fuselage, the coverage is good.

The window in the top of the fuselage may be a window in an emergency hatch, to minimize the number of cutouts in the fuselage for structural reasons. It should have a flat optical glass, *i.e.*, with minimum refraction when any sight is taken. This window is generally used for celestial navigation. A more satisfactory arrangement is a navigation turret, whether fixed or retractable. The latter is more frequently used, at the insistence of the aerodynamic experts. That is why there is no turret if there is no room for a retractable one. The turret is a half sphere, rotatable 360 deg., graduated, and equipped with a sight for easy bearing readings. Even in a turret a flat optical-glass panel should be mounted at 45 deg. for celestial navigation. The turret protrusion outside the airplane body should at least be such that the navigator, from the top of his shoulder up, is outside the airplane-body line.

In order to follow the course on a map, a chart table with protractor is provided. The size of the table varies somewhat, depending on the available space. A normal-sized table is approximately 30 to 36 by 60 to 70 in. long. When the table is in one piece, the charts are stowed in a drawer under the table top. With limited space the aisle may be utilized, for example, by having a folding leaf from the navigator's table extending over the aisle. In this case the maps may be rolled up and stowed in a tube, or a suitable case may be provided where the maps can slide down the side and across at floor level, where the case may be utilized as a footrest. Then for easy handling of the charts a rod is attached to one end of the chart and hangs down into the case, the charts being thus accessible for identification and use.

Owing to the complicated computations the navigator is confronted with, he has to have certain books and tables, for which a bookcase is provided. The bookcase is usually combined with a lockup box for his sextant, binoculars, watches, etc. He also requires such instruments as air-speed indicator, an altimeter, an outside-air thermometer, and a clock, usually

combined into one instrument panel. Any instrument on this panel should be easily readable when the navigator is working at his table. The instrument panel, therefore, is located above the table at the center or toward one end.

One instrument of vital importance to the navigator is the compass. At present, the most used navigating compass is the so-called "aperiodic" compass, which is quite large for close readings and highly damped to prevent the compass chart from swinging. This compass is mounted on or recessed in the navigator's table or has its own shelf next to the navigator's normal position.

No navigator's equipment is complete without a drift meter and, when possible, bearing plates. The function of a drift meter is obvious. It may be either a horizontal or a vertical type. Its location should be such that the navigator can use it easily. Preferably it should be located next to the navigator's seat, so that he can merely lean over, make his adjustments, and read it off or stand up, lean over his table, and read it off. Which method is employed depends on the type of drift meter used.

The bearing plates are used for taking bearings, as the name implies, and for sighting against various known objects. The angular locations of the airplane relative to at least two known objects are read, and the point at which the lines intersect defines the location of the airplane. The speed and the drift also must be taken into consideration. The bearing plate may be a simple graduated plate with movable sight located at the bottom of a couple of windows on opposite sides or, as previously mentioned, a graduated turret which may be rotated through 360 deg. and located conveniently for the navigator. There are various types of instruments on the market, all consisting of a bearing plate with some kind of sight, telescopic or its equivalent.

Since the development of the radio has progressed to a point where it is practical for aircraft, it has been utilized more and more for the safety of the airplane. Many airplanes have a separate *radio operator*. As previously mentioned, he is located on the flight deck or in a separate compartment and if possible next to the pilot's compartment. Radio installation will not be discussed in detail here; it is fully treated in Chap. VIII. Radio is used in navigation by the help of the radio loop. The

radio direction finder has the usual receiving equipment connected to an antenna which is made up into a loop and is rotatable. When the plane of the loop is in the direction of a station, the signal is the strongest. Therefore, if the location of the station is known and the loop is calibrated for angular setting, it is obvious that by getting readings in relation to two known stations the location of the airplane may be plotted on the map. From this it also follows that it is possible to fly toward a station located at the destination and thus simplify the problem of navigation. A recent development of radio for navigation is the Learmatic navigator, so called by the inventor, William P. Lear of the Lear Aviation, Inc. This is simply a combination of an automatic direction-finder loop and a directional gyro. The loop maintains the direction to the station as shown on the dial, and the direction of flight in relation to the magnetic north is maintained by the directional gyro. Now, if the two scales are superimposed, the directional-gyro scale can be set to coincide with the loop pointer. As long as the two coincide, the direction of flight is right. If the scales part, this means that the airplane has drifted; the line of flight can then be corrected and thus automatically kept corrected for drift. The instrument itself is usually mounted in front of the pilot; the other equipment that is part of the Learmatic navigator may be mounted where convenient.

From the above it can be seen that it is a great advantage to have the radio operator on the flight deck near the navigator and where the navigator may utilize the radio equipment. Where it is found that the radio operator has to be located in other parts of the airplane, he has to give the bearings to the navigator over the interphone at the navigator's request, obviously a not very satisfactory arrangement.

The *engineer's*, or *flight mechanic's*, station should be located with respect to easy communication with the pilot. If it is possible to make an arrangement so that the pilot can turn his head and see the power-plant instruments on the engineer's panel, this should be done. The engineer should also be located so that, with a coordinated window location, he can see the power plants on either side of his station. The engineer's job is to see that the engines are operating correctly at all times. The equipment needed, as earlier mentioned, are the power-plant

instruments and controls and also control handles for operation of the fire extinguishers and airplane de-icer and anti-icer.

The instruments are mounted on a panel facing the engineer. The engine controls are mounted below the panel in front of the engineer or to his left. A good arrangement is to have a kind of table in front of the engineer which in turn can be used for support of the panel and engine control units. The fire-extinguisher control handles may be located next to the engineer on the wall or in the floor where there is good access to the handles. It is not necessary to have the fire extinguisher handles next to the engineer; they may be located so that any one of the flight-crew members can pull the handle when the engineer so desires. Usually the flight deck is in front of the front spar. As long as the fire-extinguisher lines have to go out to the nacelles and usually follow the front spar, a simple piping and control installation may be accomplished by locating extinguisher bottles and control valves at the rear of flight deck next to the front spar. The same holds true for the location of the de-icer controls.

SURFACE CONTROLS

It is not exaggerating to say that flying controls are in importance second only to structure. In fact, the U.S. Air Forces says that the optimum surface-control installation shall receive full consideration, even at the cost of structure.

These controls may be divided into two classes, primary and secondary. The primary controls are those for the main surfaces—the rudder, the elevator, and the ailerons—and provide the means of maneuvering the plane. The secondary controls are those for the trimming devices, usually tabs on the major surfaces. These provide the means for trimming the ship to fly level, straight, and without lateral slope. They are used to compensate for a shift in the c.g., motor torque, unsymmetrical drag, wing heaviness, etc.

A good control installation must have two important characteristics. (1) *Ruggedness.* This is essential to prevent failure or malfunctioning even under adverse conditions. (2) *Convenience to the pilot.* This is essential to prevent confusion and fatigue for the pilot at times of emergency or during a long flight.

Ruggedness.—One of the basic provisions against failure in the system is duplication of controls Thus, on practically all

large ships and many small ones, the most important control, the elevator control, is duplicated from the surface forward to the cockpit. In many planes the aileron and rudder controls are also duplicated. It is also possible in many cases to fly and land the plane by means of the trimming tabs, which, therefore, may be considered as emergency flying controls.

Rigidity is another factor of ruggedness that must be designed into the system. In the case of push-pull rods, gears, and certain other mechanical elements, there is liable to be appreciable backlash, or mechanical slop. This must be reduced to a minimum or eliminated if possible, for it is conducive to surface flutter, the nemesis of many a high-speed ship. In this respect a cable system has an advantage over other types, for the initially rigged tension in the cable eliminates any backlash at its connections.

However, the cable itself is subject to another undesirable feature, *viz.*, deflection, particularly in large ships where there are long cable lengths. The deflection in the cable alone may, at proof load, be as high as one-third the cable travel. One means of reducing this deflection is by prestretching the cable just prior to installation. This pulls the strands of the cable snugly together and tends to eliminate what might be called the mechanical slop of the twisted cable.

After the cable is installed, an initial rigging tension, usually of 70 to 90 lb. is applied by tightening up the cable by means of turnbuckles, permanently installed in the cable assemblies. Therefore, in applying load to the system up to the point where the load in the one cable is the same as the rigging load, the other cable would be unloaded and the deflection then would be only half what it would be if there were no rigging load. Applied loads that would result in higher cable loads than the rigging load would cause a cable deflection, approximately accordingly to Poisson's ratio. Consequently, it is customary to use cable sizes far larger than necessary for the actual load to be carried, solely for the purpose of reducing the stretch. For instance, in one typical case a cable capable of carrying 4,600 lb. is used where the actual design load is only 450 lb. The penalty of this method is both additional weight and increased friction, factors to be discussed later. Another method for reducing this deflection is by using a so-called "nonflexible" cable which sacrifices flexibility to rigidity. It cannot therefore be used where it is deflected by pulleys.

All brackets, supports, and structural backing must be analyzed from the point of view of deflection as well as actual strength; in many cases the consideration of deflection is the criterion of design. In fact, deflections of the structure as a whole, *i.e.*, of the wing or the fuselage, must be considered lest deflection under other than control loads be such that it causes misalignment or binding in the controls.

Convenience to the Pilot.—Along with ruggedness, the controls must be designed for convenience to the pilot. The first factor to consider is the sensing of the elements, *i.e.*, the direction in which the control wheel, the pedals, etc., must be moved for a desired maneuver of the airplane. In all cases, it is a very simple rule that governs this, *viz.:* the control moves in the same sense, or direction, as that which the airplane is intended to take. For example, the control wheel is rotated clockwise when it is desired to roll the airplane clockwise. Similarly, pushing the wheel forward noses the airplane down and pulling it back noses it up, and pushing the right pedal turns the airplane to the right. Also, the rudder trim-tab controls (usually a wheel, knob, or crank) are turned clockwise in a horizontal plane for right rudder trim, the elevator-tab control is rotated in a vertical fore-and-aft plane for trimming the airplane for nose-heavy or tail-heavy condition, and the aileron tab control is rotated in a vertical lateral plane.

As control systems become more complex and planes become larger, another factor adverse to pilot comfort becomes important, that of mechanical friction. It is introduced to a greater or lesser degree at all bearing points, even though the best "antifriction" ball bearings are used. It also materializes as internal friction in cables passing around pulleys and drums. In a cable-pulley combination the bearing friction is dependent upon the resultant load acting upon the pulley bearing which in turn increases with the cable tension and with the angle of deflection of the cable over the pulley. The internal friction of the cable results from the flexing of the cable from a straight line to an arc over the pulley and back to a straight line. This type of friction, then, will increase with the diameter and rigidity of the cable and decreases as the radius of the pulley is made larger. It is interesting to note that this flexure of the cable takes place only when the cable approaches the pulley or leaves

it and does not occur where the cable is merely lying on the arc of the pulley circumference.

The total effect of these two factors is a rapid increase in friction as the deflection of the cable increases up to some angle approximately of 30 deg., for both flexure of the cable and bearing load increase. From that point to, say 90 deg., the cable flexure remains constant; but the bearing load continues to increase rapidly, and from 90 to 180 deg. the bearing load increases less rapidly (resultant bearing load, at 0 deg. = 0; 60 deg. = 1; 90 deg. = 1.4; 180 deg. = 2).

In a high-altitude airplane the problem of friction becomes even more serious, for the low temperatures encountered tend to increase the viscosity of any lubricant in the system and alter the clearance in mechanical fits between dissimilar materials. Friction is usually not great in any one element of the system, but the various components quickly add up to an appreciable force that the pilot must overcome for even the slightest movement of his controls.

Trim-tab Controls.—As previously mentioned, mechanical slop is undesirable in a control system. This is particularly true with respect to the tab. The trim-tab control is of necessity irreversible; *i.e.*, it cannot be activated by forces on the tab. This is usually accomplished by the insertion near the tab, and the nearer the better, of some irreversible device such as a worm and gear or a screw thread. But particular care must be exercised lest backlash allow the tab to vibrate and thus introduce a great probability of flutter with consequent bad results. If a universal joint is used on the tab side of the irreversible element, it too must be free of slop.

When the plane has two symmetrically located surfaces, as is the case with all ailerons and many elevators and rudders, it is highly desirable, if not imperative, that the two surfaces be interconnected as directly and as rigidly as possible. Such interconnection tends to cancel out certain dynamic impulses that are conducive to flutter.

There is one condition that must be borne in mind in laying out the tab controls, and that is that the effect on the path of the airplane of a tab movement in a given direction is opposite to the effect of major surface movement in the same direction. For example, the rudder tab is deflected to the right, causing the

aerodynamic lift acting on the tab to be toward the left. This force swings the tab and the rudder surface to the left, resulting in the normal turning of the ship to the left.

Dependability.—A corollary of the ruggedness in a control system is general dependability. This is based upon longevity and ease of inspection and maintenance. Consequently, it is necessary to design conservatively with an eye to a minimum of wear and maximum of accessibility. Accessibility especially must be considered at two stages in the development of an airplane. The first, naturally, is in the preliminary design of the controls, and the second is in the final assembly of the airplane itself. Usually, the controls are installed early in the assembly procedure. Later come the hydraulic and vacuum lines, electrical wiring, and miscellaneous installations, all worked out on the first airplane and frequently placed over vital inspection points of the control system unless supervision prevents this.

A fairly recent addition to the control system is the control-surface lock. Its purpose is to lock the surfaces in a fixed position when the ship is parked, so that gusts cannot pick up a trailing edge and smash the surface against the stop. But this remedy for one mishap introduces the possibility of another and an even greater accident, *viz.*, taking off with the control surfaces locked. On the face of it, it seems that no pilot could do such a thing, but experience has proved that it is all too apt to happen. Consequently, the lock, or its control, must be so designed that it is impossible to take off with the controls locked. This is sometimes accomplished by so arranging the control-lock control that it is most obvious to the pilot in his seat, either by sight or by "feel," or by so combining the lock with the throttles that they cannot be opened with the lock engaged. The latter method is the most certain, but it has the disadvantage that the engines cannot be "reved up" without the surfaces being free to blow.

One other precaution in the design of the control system is worth mentioning before closing this discussion on controls, and that is that the hookup of the system must be foolproof. Whenever you hear of an airplane with crossed controls you have heard of a case of faulty design. If it is humanly possible to hook up the system improperly, sometime, somewhere, somebody will do it. This can be guarded against only by so arranging rod

or cable lengths, end fittings, and other attachments that they will not go together except in the proper order. Sometimes this effect is accomplished by painting matching connections a common color.

In summary, the cardinal virtues of a surface-control system are ruggedness, convenience, low mechanical friction, accessibility, and plain old-fashioned foolproofness.

Automatic Pilot.—The necessity, previously mentioned, of eliminating pilot fatigue as far as possible brought about the development of the automatic pilot. This is a device that keeps the airplane on a predetermined course by correcting its flight attitude to a reference base established by one or more universally suspended gyroscopes. The automatic pilot relieves the human pilot of all physical exertion in normal flight, making it necessary for him only to observe and occasionally to correct its operation. However, as an emergency measure, the forces of the automatic pilot are always limited to the degree that the human pilot can overpower it if necessary.

Because automatic flight control is so important for the airplanes of today, the most commonly used automatic pilot, the Sperry pilot, will now be described briefly.

The Sperry pilot provides complete automatic control for level flight, on all the axes, directional, longitudinal, and lateral. It consists mainly of two units: an instrument unit consisting of gyros, an air relay, and oil valves, called the "control" unit, and located in the pilot's instrument panel; and one hydraulic Servo unit, installed in the surface controls connecting directly into the cables. The automatic pilot is vacuum and hydraulically driven. Therefore, it has auxiliary equipment such as pressure regulators and filters.

The function of the Sperry pilot, as the Sperry Gyroscope Company say in their instruction book, may be likened to

> . . . The human body, acting on the controls through its "brain," "nerve" and "muscular" system in much the same manner as the human body does.
>
> The control gyros are like the "brain," the Servo unit the "muscle," and the air relays and oil valves are like the "nerve system" that ties the "brain" and the "muscle" together in order to obtain action and control. The follow-up system is also part of the "nerve system," carrying information back to the "brain" from the "muscle."

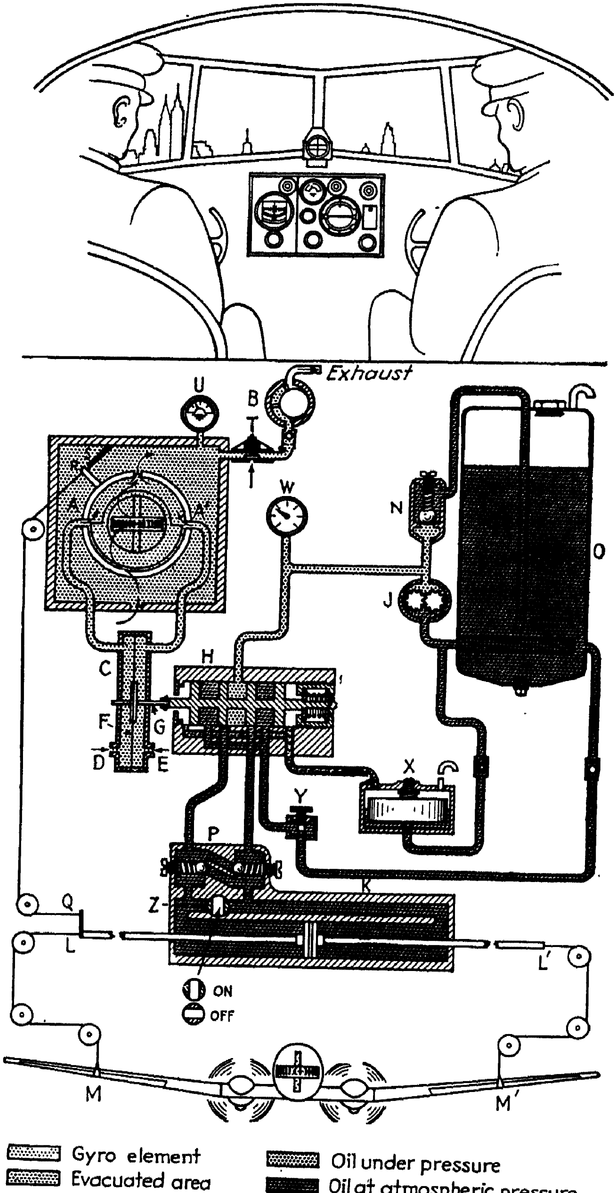


FIG. 1.—Sperry Gyropilot schematic diagram—airplane in level flight.

The action of the follow-up is such that control is applied in proportion to disturbance and over-controlling of the airplane is prevented.

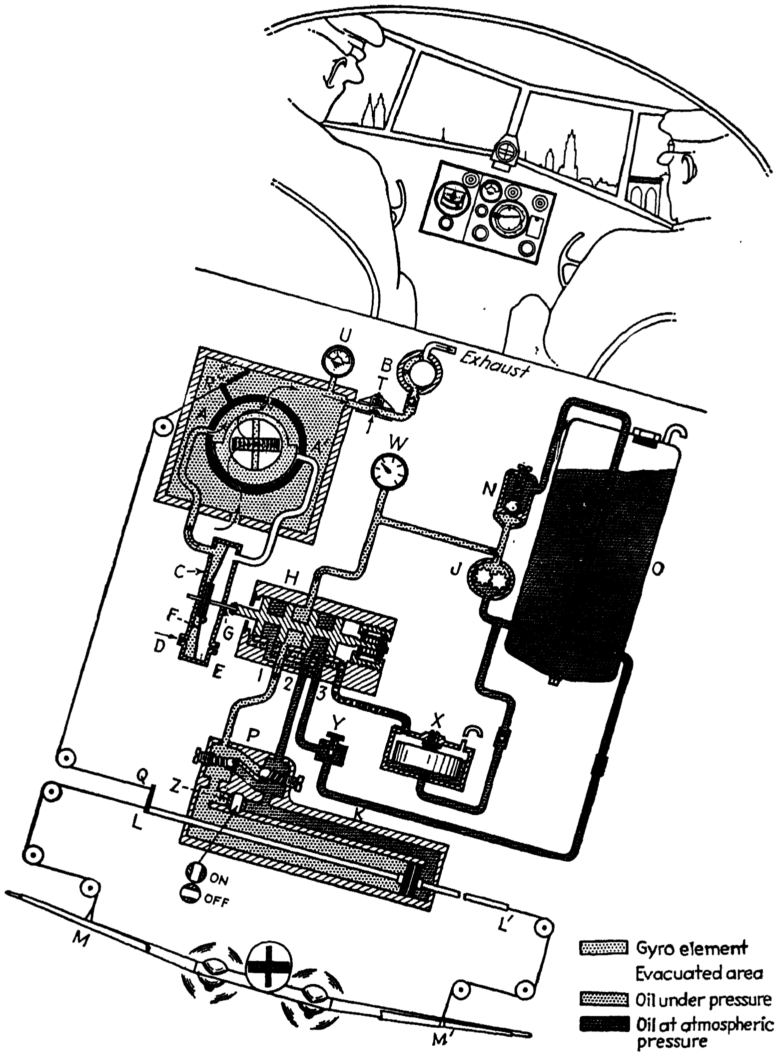


FIG. 2.—Gyropilot schematic diagram—airplane in flight with right wing down.

There are two gyros in the control unit: one for directional stability, the directional gyro, which has its axis in the horizontal plane; and one for lateral and longitudinal stability, the bank-and-

climb gyro, which has its axis in the vertical plane (see Fig. 1).

When the airplane changes its attitude, the gyroscopes maintain their relative location in relation to the earth; *i.e.*, the axes still are horizontal and vertical, respectively. The casings for the gyros, of course, move with the airplane. These motions between the casings and the gyroscopes operate air valves to the air relays. The air relays operate the oil valves that govern the oil supply to the Servo unit and supply oil to one side or the other of the cylinders for corrective motion. The Servo unit consists of three cylinders, one for each surface (see Fig. 2).

Three follow-up cables connected to the pistons in the Servo unit operate the three air valves in the control unit. In controlling an airplane, it is necessary not only to apply control to bring the airplane to level, when it has been disturbed, but also to begin to remove the applied control when the airplane is returning to level, so that, when level, the control surfaces are in neutral. Also, the amount of control applied should be in proportion to the displacement of the airplane. All this is necessary for the manual control; for the automatic control, movements and reverse corrections are handled by the follow-up between the Servo unit and the air valves in the control unit.

INSTRUMENTS

In the past, when aircraft were smaller and much simpler in construction, the pilot was able to carry out flight operations with the use of only a few instruments, *viz.*, the *tachometer*, *air-speed indicator*, *altimeter*, and *compass*. By use of these instruments, together with the development of a sense of "feel," the pilot's task of performing various maneuvers was readily accomplished.

But the continual search for greater safety and tactical usefulness and increased economy in operations has imposed numerous precision requirements which aircraft engineers have had to work to. The development of various devices to satisfy these needs has resulted in practically eliminating all guesswork on the part of the pilot and crew in carrying through their respective duties.

Among the most vital factors that the pilot and crew base successful flight operations on are (1) the proper functioning of the power plant (engines and accessories) and various items of

equipment and (2) a complete knowledge of the attitude of the airplane in flight. To this end every possible effort has been made to provide the pilot and crew with a visual indication of the operating condition of the airplane in general. The instruments used in present-day aircraft are numerous. The following discussion will consist mainly of a brief description of the most important instruments and their use.

The most commonly used aircraft instruments may be divided into two groups.

Group *A*—engine instruments.
Group *B*—flight instruments.

Group *A*

1. Tachometer.—Used to record the revolutions of the engine crankshaft in terms of r.p.m.

2. Fuel-pressure Gauge.—Measures the pressure at which the fuel pumps are delivering gasoline from tanks to the carburetors.

3. Oil-pressure Gauge.—Measures the pressure at which oil is being forced into moving parts of engine.

4. Manifold-pressure Gauge.—Indicates the pressure inside the engine intake manifold in the block, and that the mixture of the fuel and air is being supplied to cylinder ignition chambers.

5. Carburetor Air-intake Pressure Gauge.—Records the pressure at which intake air is being supplied to carburetor for necessary atomization of fuel.

6. Torque Meters.—Also commonly known as "horsepower" meters; used to measure in inch-pounds the actual torque of the engine crankshaft. At the present time, this instrument seems to provide the most accurate data on the output by each engine.

7. Temperature Gauges—Oil, Fuel, Free Air, Carburetor Air-intake Temperature.—Generally of the electric type, based on the principle of the Wheatstone bridge. A metallic bulb enclosing a resistor is installed in the medium to be measured, a current is developed across the indicator, and the resistance measured is in proportion to the temperature at the bulb.

8. Thermocouple Indicators.—Generally used to measure engine cylinder-head temperatures. They consist mainly of a long lead in which are housed two dissimilar metal wires. The engine end of the lead is connected at the base of one or more

spark plugs; and when heat is applied, a very small e.m.f. is generated in the two wires. This e.m.f. is proportional to the heat applied and is measured at the indicator in terms of degrees of cylinder temperature on a galvanometer calibrated for such readings.

Group *B*

1. Altimeter.—Essentially a barometer. However, for withstanding the various service conditions and airplane vibrations, its construction is much more substantial than that of a barometer. The use of this instrument is quite obvious, being to determine the height above sea level or any other reference plane.

2. Airspeed Indicator.—Records relative air speed, *i.e.*, the actual speed of the air flowing past the airplane in flight. The operation principle involved is that of measuring the difference between dynamic and static air pressure. By venting these to the instrument a differential pressure is obtained that is proportional to the velocity of air, or vice versa, to the velocity of airplane. By calibrating the instrument dial in terms of m.p.h., the relative air speed can be measured. For determining "true" air speed, corrections for temperature and density of air, *i.e.*, altitude, must be made.

3. Turn-and-bank Indicator.—Indicates the direction of a turn or a bank in flight. The operation principle is based upon the use of a fixed gyroscope. The gyro is driven by a vacuum and maintains a fixed position. Any roll movement of the airplane or any turn is indicated on the dial. This instrument and the artificial horizon are the basic instruments *for maintaining level flight.*

4. Rate of Climb.—Similar to the altimeter except that it uses a static air-pressure source only admitted to the diaphragm through a small orifice. By means of a very sensitive metallic diaphragm, any fluctuation in pressure is magnified by a linkage to the "indicator" pointer, which moves across a scale graduated in terms of feet per minute, thus indicating the rate of climb of the airplane.

5. Directional Gyro.—Operation based on the use of a fixed gyroscope, run by vacuum with its axis in a horizontal position. Any rotation of the airplane around the vertical axis is indicated on the card which is graduated in degrees, like a compass.

6. Artificial Horizon (Flight Indicator).—Like the turn-and-bank indicator and directional gyro, principally a gyroscope. However, it differs from the others in that the gyro is of the free-swinging type with its axis vertical. This instrument gives indication of the longitudinal and lateral position of the airplane in flight and is run by means of vacuum.

7. Compass. *Magnetic Type.*—Needs no explanation.

Radio Compass.—Used in conjunction with the direction-finder equipment previously explained.

Instrument Location and Arrangement

Location.—The instruments just discussed are specifically located to provide the crew members with information relating to their particular duty. The usual locations in the large transport type of airplane are at the pilot, co-pilot, and engineer's stations.

The pilot's and co-pilot's instruments consist in general of complete flight instruments and some engine instruments, such as tachometers and manifold pressure gauges. The engineer's instruments include all the engine instruments as previously discussed.

Arrangement.—The arrangement of various instruments on the panels has become a problem of importance. This requirement is basically due to the increased use of aircraft under adverse weather conditions when it becomes necessary to fly entirely "on instruments," generally referred to as "instrument flying." Under these conditions the pilots and members of the crew receive complete information as to the attitude of the airplane through the use of their instruments. With the continual use of these instruments for hours at a time, it becomes vitally necessary to arrange them in a consistent manner so as to minimize eye travel for the pilots and crew members and further to reduce pilot fatigue.

Several basic arrangements have been developed and used for pilot's and co-pilot's instrument panels. The most commonly used at present are the Stark and Day systems which are named after their inventors. They both divide the flight instruments into two categories, (1) rate instruments and (2) amount instruments, both arranged in horizontal lines across the pilot's and co-pilot's panels. The Stark system places the rate instruments

in the upper row and the amount instruments in the bottom row; the Day system reverses this. Once a pilot gets used to one system, he can see the airplane attitude by merely glancing at the six instruments without reading them off to know that he is flying correctly (see Fig. 3).

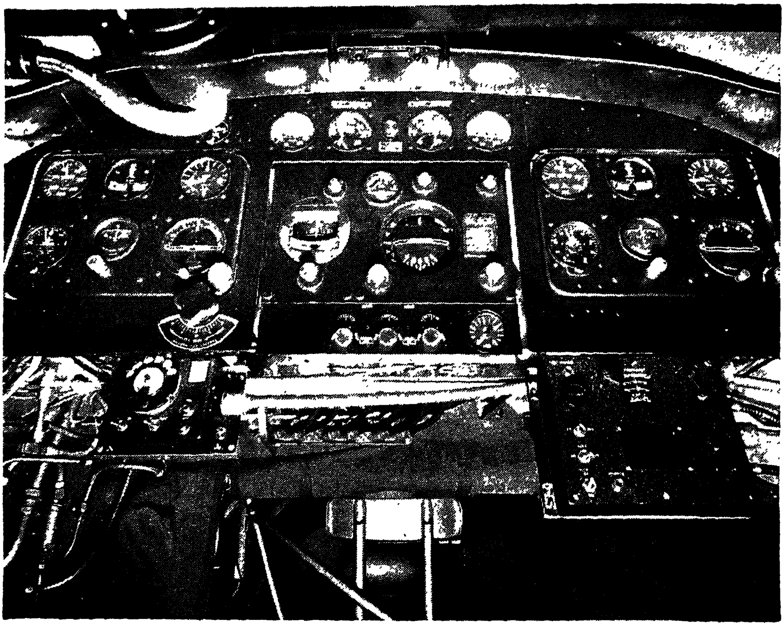


FIG. 3.—Typical pilot's instrument panel.

Difficulties.—It would be advantageous to adopt one system and use it as a standard for all airplanes. So far such standard has not been adopted, for all systems hitherto devised are subjected to various difficulties. Some of these are as follows:

Physical Limitations of Available Space.—This difficulty is due to primary design restrictions on the size of the fuselage, or hull, in the vicinity of the instrument panel. These make it necessary to divide the panel into several component units and render it impossible to make the pilot's and co-pilot's panels alike. It is much more desirable to install the complete panel as an integral unit.

Customer Requirements.—Various customers have preferred one system to others. It is believed that this condition will be eliminated in the near future.

FIRE EXTINGUISHERS

The airplane is more susceptible to fires than is any other means of transportation. Although the transition in airplane design from the wood-and-fabric type of construction to metal has done a great deal to minimize the fire hazard, there is still need for effective means of extinguishing open flame fires.

The principal sources of fires are

1. Engine-accessory compartments.
2. Hull, or fuselage, compartments.

The causes for fires are many but are principally

1. Engine backfire.
2. Overheated accessories.
3. Discharge of static electricity or electrical short circuits.
4. Human errors.

The most practical and therefore most commonly used fire-extinguishing equipment is the carbon dioxide (CO_2) system. However, there are other mediums used such as carbon tetrachloride and methyl bromide. The latter is not often used in the United States owing to its poisonous effects and, when used, is generally confined to engine nacelles away from fuselage. However, this system is often used in England.

The carbon tetrachloride is used for hand fire extinguishers only. It is a liquid and is pumped into the flame which it suffocates. It is mainly used for "spot fires" in the hull, or fuselage. For additional safety, portable CO_2 fire extinguishers are mounted in sections of the airplane where there are apt to be larger fires, such as on the flight deck.

The most frequent source of fire is the engine-accessory compartment. The protection against fire in this compartment is accomplished by piping CO_2 from a fixed bottle, usually containing $7\frac{1}{4}$ lb. of CO_2, controlled by a valve accessible to a member of the crew. One pound of CO_2 is enough to protect 9 cu. ft. of space. Usually one $7\frac{1}{4}$-lb. CO_2 bottle is used for each pair of engines. Therefore, when more than one engine is to be protected, a selector valve has to be installed so that the operator may direct the CO_2 to the nacelle on fire. The operator is usually the engineer, as previously mentioned.

For efficient distribution of CO_2 in the nacelle, the CO_2 is piped into a ring going around the accessory compartment, the ring being located in the forward section. From this ring the CO_2 is then piped to the carburetor air intake. The ring has a series of $\frac{1}{16}$-in. holes drilled into it, spaced approximately 3 in. apart and located so that the CO_2 is discharged at an angle of approximately 45 deg. above and 45 deg. below the horizontal plane; that is accomplished by staggering the holes.

The bottles are charged at a pressure of 1,800 lb. per sq. in., at which the CO_2 is liquefied. When discharging, the CO_2 stays liquefied until it escapes from the holes, where it expands and forms a dense snowlike cloud, cutting off the oxygen supply and thus extinguishing the fire.

ICE ELIMINATION

Another of the hazards to overcome in flying is the ice formation on the airplane. Without any protection against ice in the wintertime or under certain conditions at high altitudes, that may occur at any time during the year, the operations of airplanes would be very limited.

To protect aircraft from the hazard of ice, there are two distinct methods that may be employed:

1. To prevent ice from forming, called anti-icing.
2. To break away or dissolve ice after it has formed, called de-icing.

The terms *anti-icing* and *de-icing* are often misused, although they designate two distinct methods. If an inclusive term is needed, *ice elimination* can be used.

Ice usually forms in the carburetors of the engines and on propellers, wings, tail, fuselage nose, or any protrusion from any surface.

Anti-icing.—The usual method of ice elimination from carburetor and propeller is anti-icing. For protection of the carburetor, the most common method is to preheat the carburetor air or squirt into it a suitable liquid such as alcohol in the amount of 3 to 5 per cent of the fuel. To prevent the propellers from icing up, a liquid, usually 85 parts ethyl alcohol and 15 parts glycerin, is metered out by a pump to the propeller and, by means of a slinger ring, fed to the blades where it is distributed over the blade area by centrifugal force.

Little success, however, has attended anti-icing methods for wings or tails, although dry surface coatings, lubricants, and continuous applications of liquids have been tried.

De-icing.—A more successful method for wings and tails has been the de-icing method. The most successful system, if not the only system for de-icing, is that of the Goodrich mechanical de-icers. These consist of a sheet of vulcanized rubber, fabric reinforced to resist tear, having one or more inflatable tubes or cells into which air under 7 to 8 lb. pressure is pumped. This vulcanized rubber sheet with the inflatable cells is called a *de-icer boot* and runs spanwise on the wings or tails. The boots cover the leading edges from $4\frac{1}{2}$ to 6 per cent of the airfoil.

The principle of operation of boots is to crack the ice and lift it up so that the air stream will carry it away. For efficient operation, when only one tube is used, such as in the case of a fin or stabilizer where the airfoil is thin, the tube is formed into a sine wave when inflated. When several tubes are used, they are alternately inflated so that the ice breaks up into smaller pieces and consequently breaks away more easily.

The air supply for the boots is taken from the pressure side of one or more engine-driven vacuum pumps, depending on the boot capacities, and is piped through separators, pressure-relief valves, and check valves to a distributing valve. This is driven electrically and controls periodical inflation and deflation of the tubes in the boots through suitable piping between the valve and the boots. All piping and operating units are, of course, inside the airplane structure. One complete inflation-deflation cycle of all boots is 40 sec. This time has been found by experiments to be the most efficient.

To get a more distinct difference between inflation and deflation, vacuum is introduced through the distributor valve into the boots. This suction also holds the boots flat against the leading edge when not used for de-icing.

The vacuum on the tubes, however, is not enough to hold the boot down—it has to be vented properly. The venting is, of course, not through the tubes, but between and above or below, as the case may be, in the area between the tubes and the hold-down, or fairing, strips. This area is called the *elastic* area; it stretches when tubes are inflated, speeds up deflation, and also maintains tension in boots when not in use. The proper venting

can be found only through wind-tunnel tests or "tryout" on actual installation.

If there are not proper venting and deflation of tubes when boots are not in use, a very smooth boot construction throughout the width, and smooth transition from boot to wing, these deficiencies will adversely affect flying and particularly stalling characteristics. This one point cannot be overemphasized.

Any object with relative velocity through a medium such as air is subject to the collection of static electricity. The rubber boots are no exception. Such electricity would arc to the structure and thus burn holes which would soon be the cause for failure of the boots. To prevent this, a colloidal solution of graphite is coated on the outer boot surface to ground the boot to the wing and prevent any difference in potential between structure and boot.

PROVISIONS FOR COMFORT OF PERSONNEL IN MILITARY AIRCRAFT

Until quite recently, little attention was given to the comfort of military aircraft personnel even in long-range patrol boats which are frequently used as living quarters for the flight crews during extended operations. However, knowledge gained from the Second World War in Europe has caused a change in this attitude. It has been learned that the ability of a flight crew to achieve the purpose of its mission successfully is greatly hindered by fatigue and the loss in efficiency caused thereby.

The original attitude is difficult to excuse. The precision needed for bombing, observation, and defensive and offensive gunnery requires the utmost effort. To send men out for a flight of several hours to an objective that they reach half frozen, temporarily deafened, and weary from fatigue and then expect them to produce their best performance is as thoughtless as sending a track squad to an important meet in an open rattletrap of a car and expecting them to run up new records and come home winners.

However, United States military aircraft now are equipped with soundproofing, adequate heating and ventilating, and comparatively comfortable quarters. But the addition of these comforts has not eliminated any of the equipment already included in military airplanes, and therefore the job of the designers and builders has been considerably increased.

A brief discussion of soundproofing, heating, and ventilating of aircraft, the purpose and method of installation of each, and their influence on general aircraft design will be of considerable value in orientating the newcomer in the field. These subjects will therefore be treated in more detail.

Soundproofing.—Soundproofing, as the name implies, is the design and treatment of aircraft cabins to reduce the noise level inside the cabin or operating quarters. The sources of noise that must be reduced, in the order of their importance, are

1. The propeller or propellers.
2. The engine or engines.
3. Air-borne noise and noise caused by air flow over the cabin.
4. Miscellaneous rattles and superficial noises caused by vibration of equipment, etc.

Propeller Noise.—Because no quiet substitute for the conventional propeller has been contrived, design for quiet must necessarily aim toward minimizing the sound produced by the propeller. Toward this end, clearance between the propeller disk and the fuselage, or hull, is of prime importance. In general, 10 to 14 in. clearance is considered the minimum amount; reduction of this clearance increases the sound intensity as the inverse square of the distance and greatly increases the problem of insulating the cabin wall in the plane of the propeller.

Because the region of greatest propeller noise is that extending from approximately 3 ft. forward to some 5 ft. aft of the propeller disk, this portion of the cabin requires the heaviest sound insulation. In commercial airplanes the interior arrangement usually deals with this area by including it in a baggage compartment isolated from the passenger cabin; but in military aircraft this cannot be done, for the flight deck must often be large enough to accommodate an engineer, navigator, and radio operator in addition to the pilot and co-pilot, as previously mentioned. Therefore, the best must be made of a bad situation.

The propeller noise consists principally of a fairly low frequency pulsation and the harmonics thereof. A rigid section with deadened panels is the best method for minimizing the transmission of these vibrations.

To provide the desired rigidity, a small (50-in. or less) radius of curvature is desirable. When such a small curvature is impossible to achieve, as in the case of large hulls, or fuselages,

then this area must be stiffened with stringers to obtain the desired rigidity. Above all, it is important to avoid placing windows or hatches in this area, for these do not permit the treatment ordinarily attached to skin and stringers and therefore lessen the effect of the whole soundproofing treatment by allowing the passage of noise.

Aside from providing for rigidity of structure, little more is done to insulate this propeller-noise area except that in this region an intermediate layer of soundproofing is installed, as described later.

Engine Noise.—Engine noise consists of exhaust explosions and engine clatter. Though originating farther from the cabin, these noises are readily conveyed to it by vibration and through the leading edge of the wing which acts as a speaking tube. Vibration is best minimized by correct shock mounting of the engine between the engine and engine mount, between engine mount and wing structure, or both. Care must be taken that no resonant frequency between the engine and supporting structure occurs at normal operating r.p.m.

Air-borne Noise.—Air-borne noise entering the fuselage, or hull, from the leading edge is difficult to reduce, for the multitude of pipes, cables, conduits, etc., in the leading edge renders the insertion of a soundproofed bulkhead in the leading edge highly impracticable if not impossible. This explains the practice of insulating the leading edge opening from the flight deck by placing the aft partition of the flight deck forward of the leading-edge cutout. In addition, sound-absorbent materials cemented to the inside surfaces of the leading edge near its inboard opening help to reduce the noise level actually entering the fuselage, thus decreasing the final sound level in the flight deck.

Noise caused by the passage of the airplane through the air is relatively unimportant and is best reduced by good aerodynamic design.

Miscellaneous Noise.—Miscellaneous rattles and other superficial noises are important. Care should be taken in the design of brackets and furnishings to avoid flimsy installations, loose fasteners, etc. Oddly enough, one severe rattle can render speech difficult in a cabin that is otherwise comparatively quiet!

Measurement of Sound.—In the foregoing discussion the word "noise" has been freely used. At this point, it will be defined

in measurable units so that the reduction of sound levels may be better understood.

The measurement of a sound level is merely a comparison of the energy of that sound with the energy of a sound which is barely audible to the average human ear, this energy being expressed in units of pressure. The unit is called the *decibel.* According to the standards adopted by the Acoustical Society of America, all sounds are measured in terms of decibels above a reference level of 1×10^{-16} watts per sq. cm. To illustrate, a sound that consists of twice the energy of the threshhold level is expressed as 3 db, this latter sound energy doubled is 6 db, etc.

Thus, if one whistle produced a sound measuring 70 db, two such whistles sounding simultaneously would produce a sound measuring 73 db, four would measure 76 db, etc. Therefore, the job of reducing the sound level in a cabin from 110 to 80 db requires the insulation and absorption of a great deal of sound energy.

Difficulties of Soundproofing.—To complicate the task further, sound has several other peculiarities.

Assume an absolutely soundproof room, with one door outside of which a noise source produces a sound of 100 db. With a sound-level meter we measure the sound inside the room with the door open and find it to be 100 db. Then we gradually close this door, recording the sound levels at various degrees of closure until the door is open by only a 0.01-in. crack down its length. We shall find that down to this small opening we have succeeded in reducing the sound only 10 db. However, if we completely close the door, we have cut the sound to 0 db. It is obvious that airplane cabin doors must be well sealed and that windows and soundproofing cutouts must be held to a minimum.

Now let us consider a room similar to that described above, but with its interior walls absolutely nonabsorbent. Again we shall use the 100-db sound source and shall provide only a very small hole to permit the passage of sound into the room. With the sound source in operation, we record the sound level inside the room at intervals and find that the sound level in the room is gradually increasing until it finally reaches the same intensity of the source of 100 db.

These characteristics make soundproofing extremely difficult. In aircraft, we have a sound source outside the cabin that is

some 30 to 40 db higher than the desired cabin sound level; we cannot make the cabin walls absolutely soundproof, and so the sound can build up inside the cabin till it equals the 110-db source unless we can absorb the sound that does come through the walls just as fast as it enters. This we can do to a certain extent by providing a highly absorptive interior treatment; but because sound absorption is a function of absorbing area, as well as of the absorbing material itself, and because the cabin of an airplane is comparatively small, the amount of absorption in the cabin is necessarily limited.

Thus, compromise is necessary. Because we cannot eliminate windows entirely, it is futile to throw any more weight into side-wall insulation than will restrict the sound transmitted through the walls to the amount entering by way of the windows. True, double windows greatly reduce the sound entering by way of the windows. But they are difficult to make, and they represent a certain increase in weight and complicated production; and so, though they are used on transport airplanes, they are not generally employed.

The absorption we can provide inside the cabin is limited to the comparatively small area that is not consumed by equipment, windows, etc. Thus, we wind up with a sound level which does not entirely meet that desired but which is, nevertheless, a great improvement over the levels which would prevail if no attempt at soundproofing were made.

Soundproofing Treatment.—A description of a typical soundproofing treatment will now be given. To dampen skin vibration a ½-in. insulating quilt is cemented against the inside surface of the skin, usually also covering the stringers, and is attached with a semiplastic dumdum, or cement. The interior-finish layer consists of a durable flameproof fabric backed by a layer of quilted insulation, these materials being sewed together at the edges where a 1-in. hem provides neat closure of the edges. This interior layer is attached to the inboard flange of belt frames and soundproofing substructure with miniature Lift-the-Dot or glove fasteners, depending upon the requirements of headroom, etc., so as to provide an easily removable finish permitting access to the structure for inspection, subsoundproofing installations and lines, etc. Thus the combined depth of stringers and frames serves as the factor determining the amount of air space between layers of insulation.

Structure and Installation.—Typical structure generally consists of $\frac{7}{8}$- to 1-in.-depth stringers and frames that are usually $1\frac{1}{2}$ in. deep; a total space of $2\frac{3}{8}$ to $2\frac{1}{2}$ in. exists between the inboard face of the frames and the fuselage skin. In the area of most intense propeller noise, this space is divided into two air spaces by the insertion of a stretched blanket of felt or seapak quilt hung between frames. To provide the maximum space obtainable the skin-dampening material is cemented only to the skin between stringers in this area, thus providing two approximately 1-in. air spaces. This three-layer treatment provides the additional insulation required to render the effectiveness of the sound insulation in the propeller-noise area equivalent to that in the remainder of the compartment.

Bulkheads which form the front and rear closures of soundproofed compartments also receive the two-layer treatment, though the spacing between the back surface of the interior layer and the bulkhead web is usually held to approximately $1\frac{1}{4}$ in. or sufficient entirely to cover all angles, channels, etc., that are attached to the interior side of the bulkhead web.

The Lift-the-Dot and glove-fastener type of interior attachment is not so desirable as the molding strips commonly employed in transport airplanes. It has been adopted mainly as a production and servicing expedient for military aircraft, in spite of the resultant loss in insulation value of the interior layer that is inherent in a spaced type of attachment.

Because the interior finish has been designed to permit ready removal, it follows that all installations with the soundproofed sections must incorporate brackets which permit the necessary cutouts in the interior finish and at the same time provide a flange for the attachment of the surrounding interior finish. For this purpose, several types of installation bracket have been devised.

For furnishings that are complete units such as electric panel boxes and lockers and that can be mounted directly against the inboard flanges of stringers, the cabin space consumed being thus reduced, a $\frac{3}{4}$ by 1-in. angle is provided on all sides of the unit to provide a continuous 1-in. flange flush with the inboard face of the frames.

For units that require a shelf type of bracket for support, subsoundproofing brackets attached to stringers are arranged so that a sheet of metal will back up the area in which sound-

proofing cutouts are required. A layer of $\frac{1}{4}$-in. felt is cemented to the back side of this plate prior to its installation on the subsoundproofing brackets so that the area of interior-finish cutout will be insulated. This sheet is flush with the inside surface of the adjacent frames and is sufficiently large to provide a surface that extends beyond the area covered by the equipment item, attachment of the edges of the required cutout in the interior finish being thus facilitated.

In other cases a single point of support such as for a corner of a table will fall so near to a fuselage frame that a clip on the side of the frame will suffice as a subsoundproofing bracket. Because this is so close to the edge of the soundproofing panel, merely a notch in the edge of the panel is required.

From these basic types of attachment a multitude of specific variations may be designed that fulfill the requirements of closure of interior-finish cutouts combined with the provision of the necessary backing for attachment. In all cases of installations of furnishings through soundproofing, consultation with the group in charge of soundproofing installation is advised.

Heating.—Flight at high altitudes is becoming more and more common, and high altitude is always attended by cold, requiring adequate facilities for heating the stations occupied by the personnel.

The heating of aircraft has been a difficult task, and until quite recently no practical solution has been offered. For years, designers have attempted to utilize the heat of the main engine exhausts, for this source provides ample heat for any operating condition and is ordinarily wasted. Toward this end several types of hot-air and steam-heating systems have been designed and constructed; yet, up to the present time, with the possible exception of a new type of exhaust-to-cabin-air heat exchanger which is undergoing U.S. Navy tests, no satisfactory utilization of exhaust heat has been evolved.

In all such systems a fundamental weakness is the apparent inability of present-day materials and construction methods to withstand the combined forces of the intense heat and, in the case of steam boilers, the drastic temperature changes to which the heat exchanger is subjected. Vibration is likewise a complicating factor. The exhaust-to-fresh-air heat exchanger also presents the hazard of possible leakage of exhaust gas into the

cabin-air supply which would doubtless be disastrous. Thus the exhaust heat from the main engines is still going to waste, and we have turned elsewhere in search of a satisfactory heat supply. Further to justify the dismissal of main-engine-exhaust heat as a source, the U.S. Navy has recently included the requirement of heating for the airplane while on the ground or afloat in order to make living aboard more comfortable. This requirement naturally means discarding any heat source that is dependent upon operation of the main engines. Toward the solution of this problem, also, there have been several attempts.

To provide heat, it is obvious that utilization of some form of fuel combustion is necessary. This can be achieved directly by the use of (1) *open-flame burners*, (2) *enclosed-flame hot-air or steam systems*, or (3) *the power from a small stationary engine to drive an electric generator* or any number of similar applications. The open-flame type of heater is inherently such a fire hazard that its use is considered impracticable.

Variations of the enclosed-flame type of heating unit have been devised. These include a heat exchanger through which air is circulated by a blower and several types of steam-generating systems which provide heated air to the cabin either from a central cabin-air blower or by the use of recirculating radiator-fan units. These also have as yet failed completely to solve the heating problem, because of excessive electric-power requirements for fans and accessories, the necessity for frequent cleaning and servicing owing to the lead deposits that occur when high-octane leaded fuels are burned, the multiplicity of controls and safety devices required to make safe the use of gasoline as a fuel, and, last but not least, the excessive weight of such equipment.

However, there is one type of enclosed-flame heater that appears to present a solution to these problems. This heater is a slight variation from the standard Stewart-Warner South-Wind car heater. This heater may be procured either in a small size suitable for use as recirculating "spot" heaters or in large sizes for use in the cabin-air supply.

Briefly the Stewart-Warner heater functions as follows: A fuel-air mixture is introduced into the combustion chamber of the heater from some pressure source that will provide a flow of approximately 2 cu. ft. of mixture per minute while maintaining a pressure drop through the heater of approximately 2 to 4 in. Hg.

An electric igniter (of glow-plug type) installed in the combustion chamber ignites the mixture, and the hot exhaust gases are circulated through a series of baffles in a heat-exchanger cylinder and thence overboard. Fins arranged on the heat-exchanger cylinder transfer the heat of these gases to a flow of air furnished by the fan provided on the heater. A simple shroud directs the blast from the fan across the heat-exchanger fins.

Because the igniter plug requires some 9 amp. at 24 volts, a ceramic disk is installed in the combustion chamber so that the fuel mixture flows through the disk. After ignition electrically the hot gases heat the ceramic disk so that it will maintain combustion of the gases. At this point the igniter, which is always on when the heater is cold, is turned off by means of a contact bimetal actuated switch installed on the extreme end of the heat-exchanger cylinder. The electric load for the fan only is approximately 1 amp. at 24 volts per heater. Combustion is maintained as long as the fuel mixture is supplied.

In some installations, several small (8000 B.t.u. per hr.) Stewart-Warner heaters are located one at each of several crew stations to provide heat; the air-fuel mixture is provided by a small gasoline-engine-driven blower which pulls air-fuel mixture through a carburetor and furnishes this mixture under pressure to operate both heaters and gasoline engine. This also provides the necessary supercharging for operating the engine-blower unit at high altitude. Operation tests at 20,300 ft. altitude have proved that this system will be satisfactory to an even higher altitude.

The gasoline-engine-driven mixture-pump assembly is shock-mounted on Lord shear-type rubber mounts. From the manifolding header on the mixture pump, $\frac{1}{2}$-in. Weatherhead hoses provide flexible connections to each of the required $\frac{1}{2}$-in.-diameter 52S aluminum-alloy mixture lines each of which is routed to and connected to a Stewart-Warner heater. Where necessary a deflector is provided on the heater shroud to direct the heated air at personnel. Exhaust lines from each heater are $\frac{1}{2}$-in.-diameter stainless-steel tubing to a point where the exhaust is sufficiently cool to allow the use of 52SO tubing. The exhausts may be routed to a common overboard exhaust.

The addition of the Stewart-Warner heating equipment to the airplane adds little to the general design problem other than its

requirement for a small amount of space at each crew station for the spot heater and the addition of the piping required.

Ventilation.—Ventilation is necessary (1) to prevent the accumulation of moisture in the cabin air which would result in the fogging of windows, (2) to provide ample fresh air to meet the physiological requirements of operating personnel, (3) to remove odors, and (4) in the case of some summertime operations, to cool the cabin.

The use of scoops in the air stream to provide ventilating air is taboo in high-speed aircraft. Hence, either the leading edge of the wing or the nose of the fuselage is used as the location for air inlets to suitable distributing duct systems. However, because ducts are sizable and require a certain minimum of cabin space, every effort is made to cut the duct sizes and runs to a minimum through the use of high-velocity air-distributing grilles such as Anemostats or Aerostats. These grilles direct the air along the ceiling or side wall, as the case may be, in such a way as to create no objectionable draft on near-by personnel. In addition, they have some aspirating effect which permits the use of rather high temperatures of inlet air for heating without the disadvantage of the hot draft that occurs when other types of grille are used.

So far as ventilating requirements are concerned, preventing the fogging of windows requires more air than any of the other purposes mentioned above. Because the human being perspires copiously, particularly when working under a nervous strain, it is important to provide ample fresh air to the airplane cabin to maintain a low relative humidity. The volume of air required will depend upon the number of men occupying a given compartment and upon the volume of the cabin to be ventilated, amounting to some 20 to 25 cu. ft. of fresh air per man per minute.

Since the physiological requirements of a man moving about comparatively little are approximately 16 cu. ft. per min. and since it is the usual practice of commercial airplanes to provide about 22 cu. ft. of fresh air per passenger to evacuate foul air and odors, it is apparent that the quantities of air supplied to prevent window fogging are ample for the other requirements of the ventilating system. Cabin cooling as yet consists only in ventilating without heating the incoming air.

The need for simplicity, speedy production methods, and light weight renders the detail design of comfort equipment difficult at best. New and special applications, such as cabin supercharging, set up new standards that must be met.

OXYGEN

Constant improvement in aircraft and engine design has made it possible for the airplane to ascend to and operate at higher and higher altitudes and under decreased barometric pressure. The development of the human organism, on the other hand, has taken place relatively close to sea level. In spite of the amazing capacity of the human organism to adjust itself to sudden changes, transporting the human body by airplane to high altitudes cannot but have marked effects on organic functions.

The diminishing barometric pressure as higher altitudes are reached affects human beings only when the partial pressure of the oxygen in the inspired air decreases to a point 14 per cent of that at sea level. This point is at approximately 11,000 ft. and is, of course, only statistical, for millions of people have become acclimatized to altitudes as high as 14,000 ft. in the mountainous regions of the Andes, the Alps, and The Himalaya. The highest altitudes to which a man can become permanently acclimatized appear to be in the neighborhood of 18,000 ft., as in the mining communities of South America; but, in general, most people exist at altitudes lower than 10,000 ft. and are only subjected to high altitudes for comparatively short periods.

All available data from medical, military, and commercial sources indicate that the need for oxygen becomes apparent above altitudes of 10,000 or 11,000 ft. As the oxygen content of the air is about 21 per cent, reducing the pressure (as at altitude) reduces the amount of air for a given volume and likewise the amount of oxygen that a person takes at a normal rate of breathing. At 12,000 ft., for example, the pressure is reduced so that a person breathes only 64 per cent as much air as at sea level and, of course, only 64 per cent as much oxygen with it. Expressed in another way, a person at 12,000 ft. would still take in air with a 21 per cent oxygen content; but, owing to the less dense air breathed, the quantity of oxygen breathed, when compared with the sea level 21 per cent, would be only 13 per cent.

The effects of a deficiency in oxygen are insidious and are seldom realized by the individual in the earlier stages. Shortness of breath, dizziness, and dull headaches are warnings that should not go unheeded. Those who are physically and mentally tired or still subject to the effects of recent use of alcohol are particularly affected by oxygen deficiency. Even moderate altitudes may be harmful, and it is reported that repeated daily exposure at altitudes of 12,000 ft. for 4-hr. periods resulted in mental and physical fatigue which persisted and was further manifested by difficulty in mental concentration, sleepiness and lassitude, lack of initiative, and increase in nervous instability. At 15,000 ft., vision, hearing, and coordination begin to fail. At 18,000 ft., pulse is rapid, blood pressure low, and collapse is imminent.

Fortunately, the ill effects of oxygen want (anoxemia) at altitude can be avoided as long as the inspired air is sufficiently rich in oxygen. The basic criterion in regard to the use of oxygen is not the point at which a pilot can operate without it but rather the point at which he begins to benefit from its use. Accordingly, one of the major air lines in this country has taken a firm stand that oxygen must be used by the crew at any altitudes above 10,000 ft., and the U.S. Navy "strongly advises the use of Oxygen at all times while participating in flights above 15,000 feet and that Oxygen be used when remaining at an altitude above 12,000 feet for periods of two hours or longer duration, and when participating in flights below 12,000 feet but at or in excess of 10,000 feet for periods of six hours or longer."

In order to keep a person, in flight at high altitude, in an environment similar, with respect to oxygen, to that at sea level, one need only increase the percentage of oxygen in the inspired air, for the partial pressure of the oxygen is correspondingly increased. At sea level, the partial pressure of the oxygen in the inspired air is approximately 159 mm.; total pressure is 750 mm. Hg and an oxygen percentage of 21 per cent; and at 35,000 ft., 73 per cent of the inspired air must be oxygen to maintain the same partial pressure as at zero altitude. It follows, then, that there is a definite limit as to the altitude one may reach and still live. This point has been established at approximately 115 mm. total pressure of mercury, or 45,000 ft.

It is on this principle of partial pressures that the various types of oxygen-supply apparatus used in altitude flights are designed.

The earliest type of breathing apparatus consisted simply of a flask of liquid oxygen from which a hose ran to a pipe bit held in the teeth of the crew member. As the liquid oxygen evaporated, a pressure was built up which caused the gaseous oxygen to flow through the hose into the individual's mouth. The difficulty of maintaining a supply of liquid oxygen and the extreme cold pressure at which the oxygen had to be breathed were among the disadvantages. However, this system was used for several years for want of something better, the only improvement being an attempt to control the temperature of the gaseous oxygen by piping it through a coil wound around an exhaust pipe.

From liquid oxygen to gaseous oxygen bottled under 1,800 lb. per sq. in. was the next step. The pipe bit, which had been extremely uncomfortable and hard to hold, was discarded for the mask. This combination of gaseous oxygen and face mask is one in which many improvements have been made and is in general use today.

In general, the fixed-equipment group are not directly concerned with the detail design of the actual oxygen-breathing equipment but usually confine themselves to designing only the installation in the airplane.

In military service, gaseous breathing oxygen is bottled under two standard pressures. One, designated as high pressure, is bottled under 1,800 lb. per sq. in.; the other, low pressure, is bottled under 400 lb. per sq. in. The trend is toward the low-pressure installation, for it was found in the Second World War in Europe that, unless armor-plated, the high-pressure bottles were extremely explosive upon being hit with a 30- or 50-caliber bullet, as much damage being done to the airplane as if it had been hit by antiaircraft fire. To offset the danger of exploding oxygen bottles, it was found necessary to armor-plate the cylinders. This, of course, was a disadvantage because of the weight.

On the other hand, the volume of gas bottled under 1,800 lb. per sq. in. is $4\frac{1}{2}$ times the volume of gas bottled under 400 lb. per sq. in. Thus, in reducing the hazard of exploding cylinders by going to a lower pressure, it is of course necessary to have

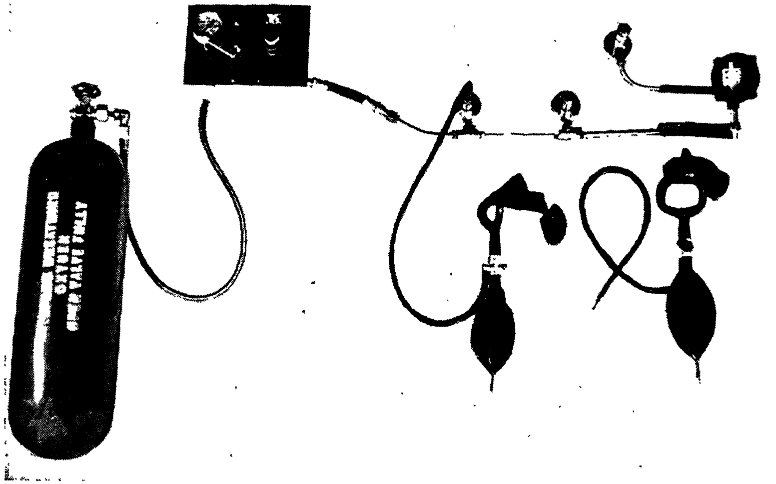


FIG. 4.—High-pressure oxygen system.

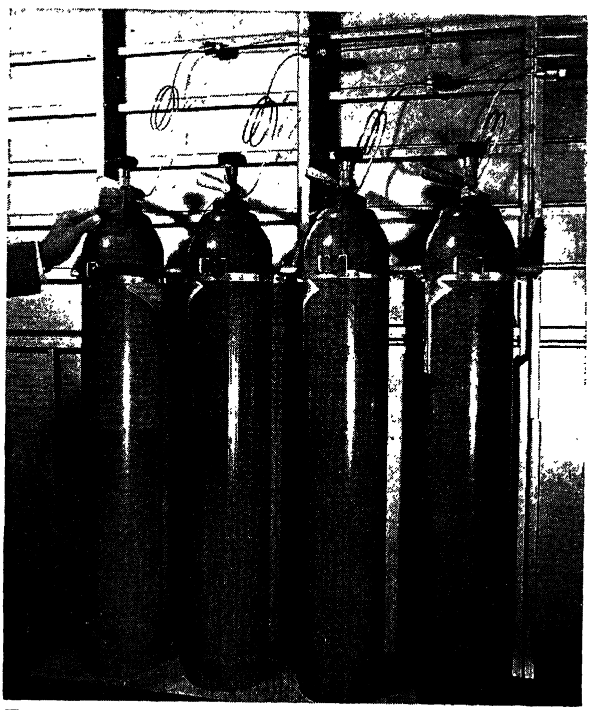


FIG. 5.—Low-pressure oxygen bottles installed in a fuselage.

$4\frac{1}{2}$ times the number of bottles. Nevertheless, it has been found that, even though a greater number of bottles is required owing to the oxygen being at low pressure, the wall thickness of the cylinders is greatly reduced and the aggregate weight of the low-pressure cylinders is in no case equal to the weight of high-pressure cylinders for the same volume.

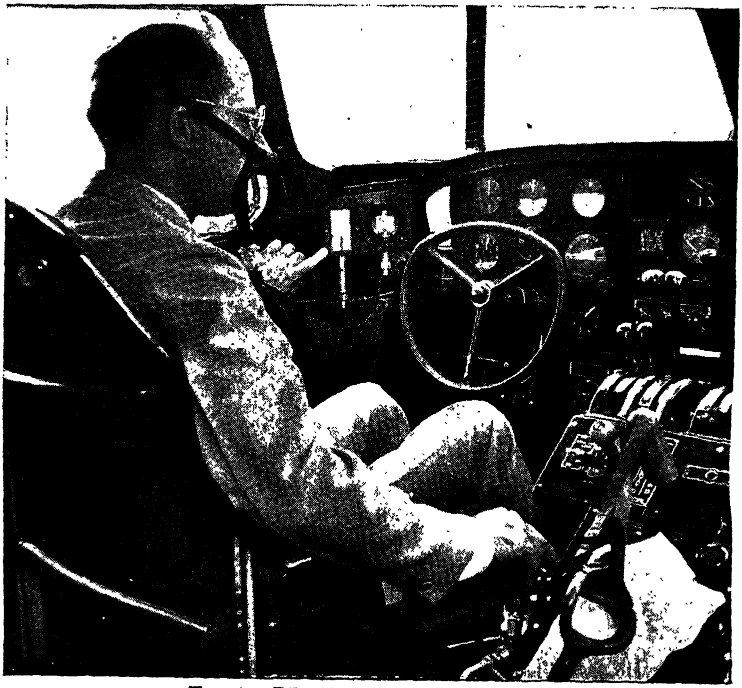


FIG. 6.—Pilot wearing oxygen mask.

High-pressure oxygen is, at best, very dangerous. When making an installation, one must remember to keep the high-pressure tubing and bottles away from any organic matter, for the right combination of oil vapor and high-pressure oxygen will explode owing to spontaneous combustion. It is difficult because of the high pressure to have the necessary ground equipment at each station to fill the bottles. Thus it is necessary that the high-pressure cylinders be readily removable. This is unhandy because of the weight and bulk of the bottles. Figure 4 shows a typical high-pressure installation.

Low-pressure cylinders may be permanently installed in the airplane and may be filled from a high-pressure cylinder on the ground by means of the necessary piping and a filler valve on the side of the fuselage. This in itself is a great advantage; because the low-pressure cylinders need not be accessible, they may be installed in out-of-the-way places that otherwise would be empty, such as the side of the wing (see Fig. 5.)

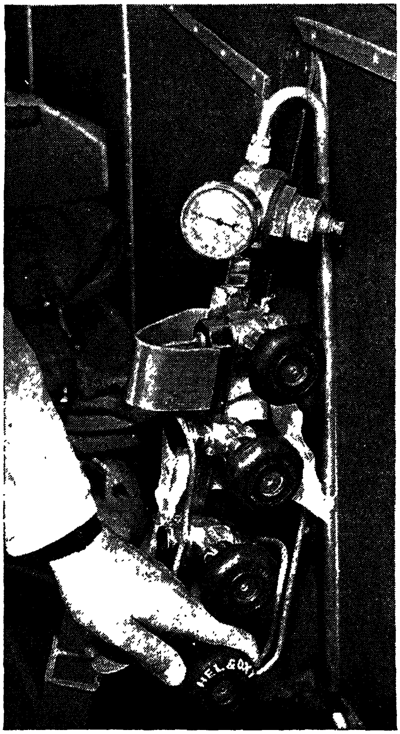
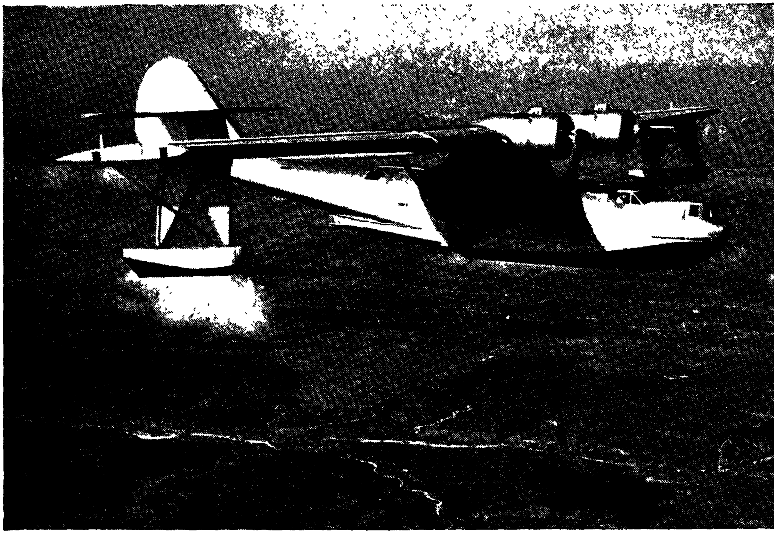


FIG. 7.—Valve manifold and pressure gauge in pilot's compartment.

Another disadvantage of the high-pressure system is the fact that the small number of cylinders reduces the margin of safety of the supply when one bottle is hit. The low-pressure cylinders being greater in number for the same given volume can be spread throughout the airplane; and even though one bottle may be hit, the greater percentage of the supply is still left intact.

Figure 6 shows a pilot wearing an oxygen mask. Figure 7 shows the valve manifold and pressure gauge.


Consolidated amphibian flying boat ready for a water landing.—(*Official Photograph, U.S. Navy.*)

CHAPTER VI

HULL DESIGN

Introduction.—Before starting to describe its design, the purposes of the hull will be summarized. The hull is really the backbone of the airplane. It must tie together the various functional parts of the airplane and therefore has all the loads on it that are imposed by these parts, such as landing gear, tail, wing, and cargo. As far as carrying airplane loads, the fuselage and hull are the same, except for the landing condition, the main difference being that loads are concentrated on the fuselage owing to the attachment of the landing gear. In the hull, landing loads are spread over a fairly large area. In addition to the structural requirements, the hull or fuselage also serves as a cover, or fairing, to enclose the cargo, crew, and equipment. Of the two, the hull is a more difficult design problem, because of two requirements, water tightness and corrosion resistance.

The latter is the more difficult problem of the two, especially for hulls that operate in salt water. Corrosion is controlled by choice of finish and material.

Preliminary Considerations.—With the functions of the hull in mind the designer goes to work. However, there are many other factors that he must constantly consider, *viz.*, weight, cost of manufacturing, aerodynamic cleanness, service ability, maintenance, and materials available. He must also allow for the general and detail specifications that the customer has set up. The general specifications are usually based on past practice. The detail specifications are based on the specific use the airplane is to have.

Determination of Shape and Interior Arrangement.—When a hull or fuselage is ready for detail design, the general shape and interior arrangement have been established. This shape has been set by a preliminary design group whose duty it is to investigate the customer's needs as to functional requirements and to check performance by wind-tunnel tests and basin tests in the case of the hull.

The thing that determines the shape of a fuselage is its cargo. In general, a fuselage is of the smallest section that will contain the desired cargo. As the speed of the airplane is a function of the drag, the problem of keeping the section of the fuselage to a minimum is a difficult one.

In the case of a hull the problem is very much the same, except that the bottom shape is determined by the necessary hydrodynamic characteristics. This will result in some sort of compromise. In general, for a similar airplane, a hull is not so small as a fuselage.

Detail Design.—With the general shape and arrangement of the interior the detail design can be started. As an example, let us take the design of a twin-engine cargo boat of 50,000 lb. gross weight. In designing the structure of the fuselage, thought must be given to the space that will be required for the controls, heating conduits, passageways, and miscellaneous equipment. This requires much layout work and coordination with the groups concerned. As a rule the controls and equipment have not been designed in detail when the basic structure is designed to provide for them. The *mock-up* (see Chap. I) a more or less detailed full-scale wooden model of the airplane, serves to give a visual

picture of the necessary arrangement of equipment within the hull and is helpful in preventing interferences.

We now have the general arrangement. Therefore we lay it out on the drafting board and start our first *basic layout*, as in Fig. 1.

The general shape having been laid out, we next locate the *bulkheads* and *belt frames*.

First we locate the ones for which there is no choice of location, *viz.*, those under the wing spars and the stabilizer spar.

We locate bulkhead 1 just aft of the nose anchor compartment. Bulkhead 2 is midway between 1 and 3. Bulkheads 5 and 6 are arranged to divide up the span of aft keel (see Fig. 1).

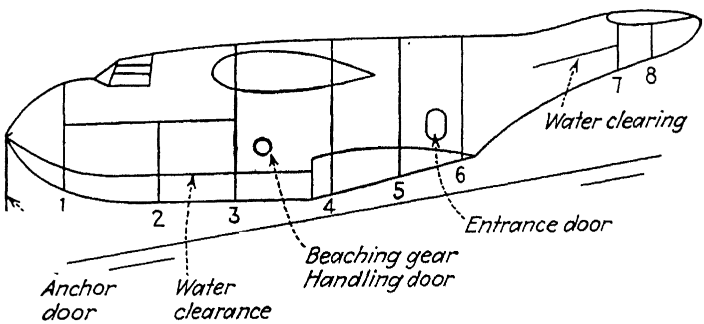


FIG. 1.—Basic hull layout showing station locations.

The reason for bulkheads is the flood condition. In a hull the bulkheads are water tight to a height of 12 in. above the flooded water line. The flood line is the sea water line with a given compartment flooded. Some specifications call for one compartment flooded. Others call for two adjacent compartments flooded, truly a severe condition.

From past experience we know that 20 in. is a good spacing for belt frames, and so we place them accordingly. As quickly as possible we locate these stations dimensionally by measuring aft of the nose.

So far we have dealt with the hull shape in side view only. Because we need all three dimensions to complete the hull design, we now start a lines drawing. A *lines drawing* is a series of transverse sections taken at station locations with a series of longitudinal vertical and longitudinal horizontal check sections. To illustrate, we shall take a few sections on our hull as in Fig. 2.

These basic sections may be taken from the wind-tunnel model, which of course will not have the exact stations we wish because of its small scale.

We now cut horizontal and vertical sections and check them for smoothness. When the job is complete, all points check in the three views.

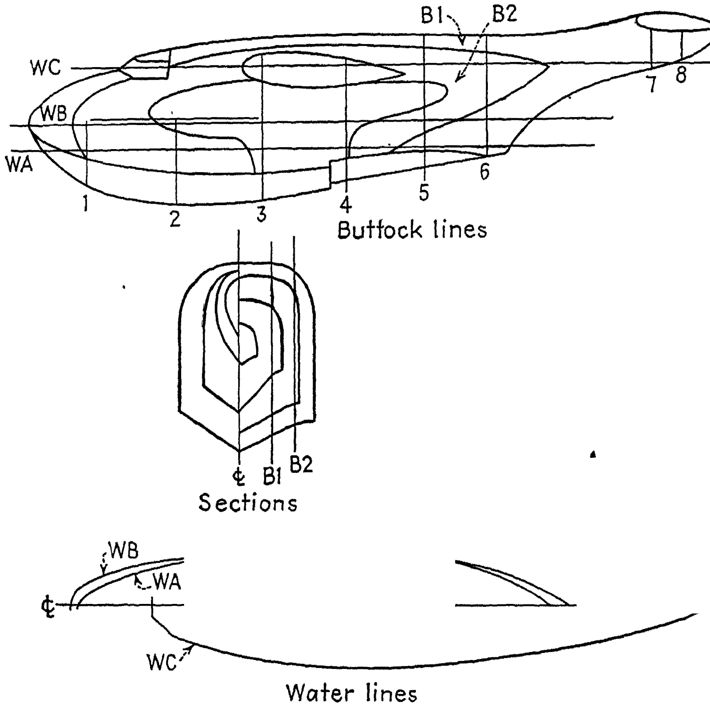


FIG. 2.—Hull-lines drawing showing buttock lines, sections, and water lines.

These lines are turned over to the loft department who expand them to half or full size and greatly improve their smoothness. They do this to obtain an exact record of the shape of the airplane for laying out bulkheads, belt frames, and other parts of the airplane.

Designing for Landing-load Conditions.—We are now ready to break down design of the airplane into a series of separate problems. To continue with the problem of the hull, we shall design the members as they take the loads of the most difficult design condition, *viz.*, landing. As a boat comes in for a landing,

it is in an attitude that approaches the stall condition. The first part of the bottom to strike the water is the step. The water load is then picked up by the parts of the hull in the following order: plating, stringers, floor frames, keel, bulkheads. This water load is the reaction of the inertia loads of the airplane.

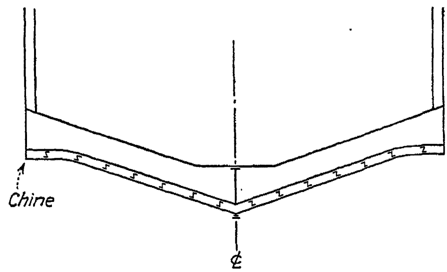


FIG. 3.—Transverse location of stringers.

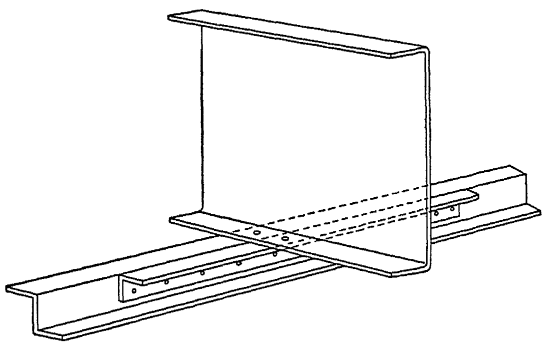


FIG. 4.—Stringer-reinforcing angle-section belt frame.

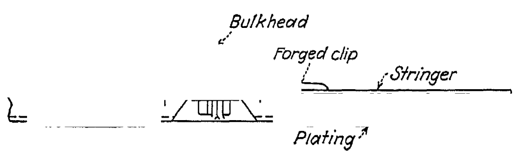
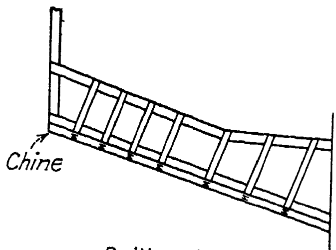


FIG. 5.—Stringer splice at watertight bulkhead.

The weight of everything in the wing (usually, wing, power plant, and fuel) is picked up by the wing spars and delivered to the hull through the fittings at the top of the main bulkheads.

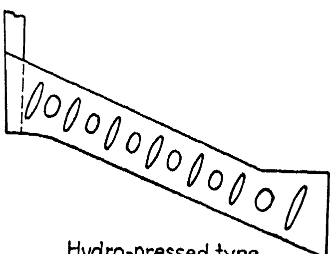
The weight of the hull and the equipment in it is carried to the bulkheads through the side plating in shear. The bottom plating covers a group of stringers that run parallel to the center line of the ship, spaced 4 to 6 in. apart (Fig. 3).

Stringers.—For weight saving the stringers are reinforced at the point of maximum bending, which is at the frame, or reaction, point. This is done by adding a member to the stringer that acts with it, usually an angle section (see Fig. 4). The stringers must be interrupted at the watertight bulkheads. This calls for a special attachment and is usually handled in the manner shown in Fig. 5.



Built-up type of floor frame

FIG. 6.



Hydro-pressed type of floor frame

FIG. 7.

Floor Frames.—Now that the bottom load is in the stringers, it must be picked up by the floor frames. The frames are beams between the side of the hull and the keel, usually figured as pin-ended at the chine and continuous at the keel. These frames may be constructed in several ways, shown in Figs. 6 and 7.

The type shown in Fig. 7 is the best from the production angle. The flat pattern is routed to shape and the flanges formed on the hydropress. Additional flange angles are added to increase the bending strength. Because these frames are of heavier gauge than built-up frames, there is always sufficient shear area. The weak point is usually the lack of flange material

which is corrected by the addition of angles placed opposite to the frame flange.

Keel.—The keel is the structural member that runs the length of the fore and after bottom. Its purpose is to pick up the major part of the frame load. (The minor part is carried by the side of the hull.) The keel is a beam loaded at the floor frames with reactions at the bulkheads. Some boats have several keels, and some keels are not continuous but span from bulkhead to bulkhead.

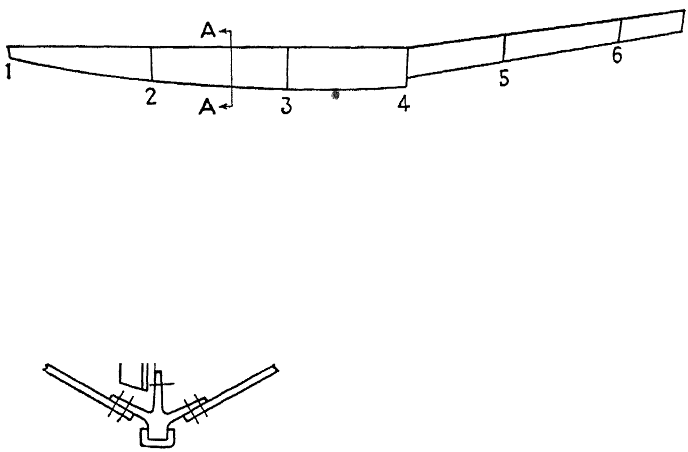


Fig. 8.—Typical flying-boat keel.

The most efficient structure seems to be a single keel continuous from one end to the other. We shall use this type in our problem boat. Figure 8 will indicate the construction. The upper flange is made of an extended T which is the minimum of flange material necessary. Straps are added where additional area is necessary. Several straps may be added to a single section. In this case the straps become progressively shorter, which constitutes a simple means of changing the section gradually. The lower flange is an extrusion so arranged as to receive the bottom plating. A rubbing strip to protect the bottom from damage is also incorporated. A removable channel is added to the rubbing strip to facilitate replacement in case of serious chafing. A section 24 in. forward of the main step is subject to the most damage and is made a separate piece. The rubbing-strip feature is used from the main step forward. The rest of the keel is

made up of web and vertical stiffeners. The stiffeners are located at bulkheads and belt frames with the necessary intermediates. The upper and lower moment ties are carried in the manner shown in Fig. 9.

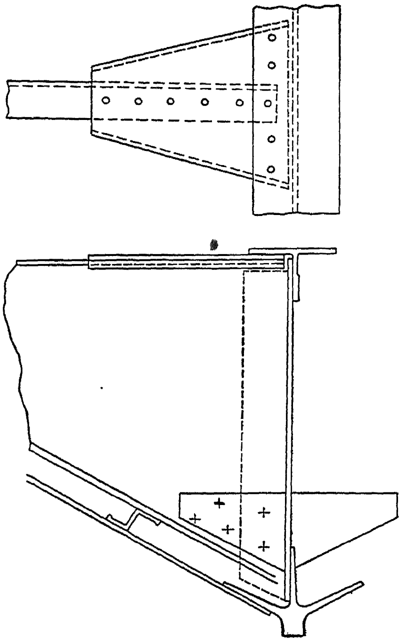


FIG. 9.—Keel stiffener tied into belt frame by means of gussets.

Bulkheads.—The bulkheads pick up the keel loads and transfer them to the side plating of the hull. A typical case would be bulkheads 5 or 6 of our problem boat (Fig. 1). In this case the keel load is picked up at the lower end of the column and led into the side plating at the upper end. A closed section is one of the best columns made. The cross section of one type is shown at the bottom of Fig. 10.

The design requirement of the web is to stand water loads due to the flood condition, which runs to a head of approximately 4 ft. Bulkheads of this nature have water tight doors, the design of which will be discussed later. The bottom part of the bulkhead has the same loads as a floor frame and is designed in the same manner. As a rule the frame portion of the bulkhead is built up to maintain continuity of web and to make it

easier to design for fore-and-aft loads due to the flood conditions.

The major bulkheads are designed in a similar manner except that the columns go directly to the top for attachment of the wing. The columns are also similar, except for their size. For our problem ship, the column loads will run around 200,000 lb. The upper fitting is usually a massive forging.

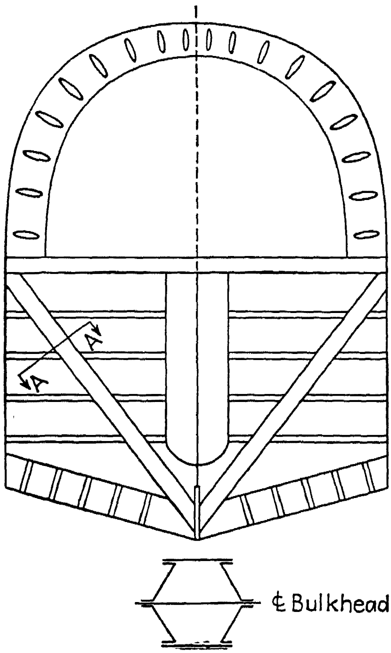


FIG. 10.—Typical watertight main bulkhead.

Other Design Features.—The foregoing covers roughly the structure to handle the direct landing loads. There are many other conditions for which the design must be checked, such as the bending of the complete hull, bow landing, side landing, and others.

One of the most important features for the designer to watch is the location of necessary discontinuities of structure. A large opening placed in a highly stressed part of the hull is always costly with respect to weight, because of the necessity for reïnforcing sections.

Cutouts.—The next thing to be considered in the hull design is the location of all the cutouts; this is not so serious a problem

in our cargo ship as it is in a military ship. There are many conditions that must be considered in locating an opening. For instance, the entrance door must be well over the load water line. It must be in a position which a dinghy can approach without danger from the propellers and at which entrance can be made under adverse weather and water conditions.

The anchor door must be placed so that it is convenient to operate lines or the anchor while the boat is taxiing. It must be clear of the propellers, and it must be in a good place for a man to make a buoy.

Flooring.—Our next problem is flooring, which may be classed as of two types, long span and short span. The kind of supporting structure is the main difference between them.

The flight floor is a good example of long-span floor. Here we run the supporting beams fore and aft between the bulkheads. This will form a trough for the control cables. We also arrange to have the beams coincide in location with the pilot's and co-pilot's seat tracks.

There are many types of floor surface used. One is a wooden floor which is used when it is necessary to incorporate soundproofing. Another is corrugated aluminum-alloy sheet. This is the lightest and strongest of any found to date. It also has the advantage of being able to carry shear. Various nonskid surfaces are also employed.

Further Items.—Additional items that must be considered in hull design include

1. Hatches and doors (seals, locks, construction, drainage).
2. Water tightness (rivet spacing).
3. Corrosion (insulating dissimilar materials, and neutral materials by means of phenolic finish).
4. Pilot's enclosures.
5. Walkway on deck.
6. Windows (cans for soundproofing).
7. Wing-to-hull attachment.
8. Belt frames, hoops.
9. Snubbing posts and boat-hook grabs.
10. Breakdown and subassemblies for production.

CHAPTER VII

BEACHING- AND LANDING-GEAR DESIGN

BEACHING GEARS

Purpose and Use.—The function of an aircraft beaching gear is to provide means of handling seaplanes and flying boats on land and to and from the water. As such, they are individually designed for each craft, to provide maximum utility.

Types. *Cradle.*—This type is used somewhat on commercial flying boats in fixed-base operations. As the name implies, it consists of a floating cradle constructed of heavy steel sheet and angles or of welded tubular construction provided with flotation tanks. Such beaching gears are normally equipped with four trucks with either the front set or both sets of wheels steerable. Wheels may have hard-rubber or pneumatic tires. The advantages of a cradle are its relative simplicity and small structural weight addition to the airplane, for the attachment fittings are not complicated. Its disadvantages are that it cannot be carried in the plane, its large size, and the need for a separate beaching crew.

Unit Beaching Gears.—This type has found favor and proved most practical on naval flying boats because of its better adaptability to a variety of beaching situations and the plane's ability to transport its own gear to new scenes of operation. Its requirements are quite rigorous and lead to many interesting design problems (see Fig. 1). Some of these are as follows:

1. The gears must be easily and quickly attachable, preferably by the plane crew with a minimum of shore aid.
2. They must have simple, rugged, foolproof locks.
3. They must float to facilitate attachment on large planes.
4. The nose or tail unit should be steerable, and it must be possible to lock the main units at 45 and 90 deg., for maneuvering in close quarters.
5. It is required that they be very rugged and resistant to corrosion and abuse.

6. It is usually desired that the gear be designed to be removed and stowed on board the ship with a minimum of labor.

Retractable.—One experimental plane has been equipped with a fully retractable tricycle beaching gear. This type, though a great convenience, is hardly justified because of space and weight requirements, except for a short-run passenger boat that must beach frequently.

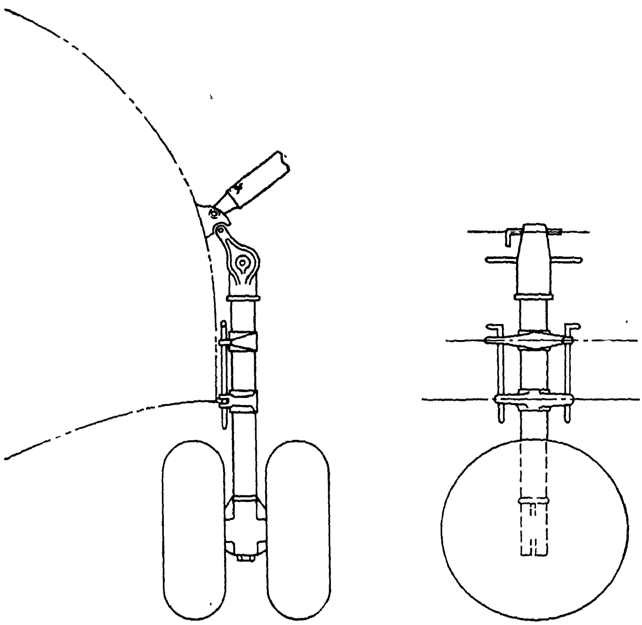


FIG. 1.—Typical flying-boat beaching gear, detachable type.

General Characteristics.—Most modern gears are provided with pneumatic tires. This has proved necessary for shock absorption and to prevent bogging on soft surfaces. Because the tires do not carry landing impacts, they may be rated for static loads of about 1.4 times the regular landing-gear rating. In some cases the tires are partly filled with water to aid submerging when being attached. Special water-filling valves are provided on the inner tubes.

Wheels may be of cast dural, cast iron, or stamped steel. Beaching gears have single or double wheels, largely depending upon which gives better clearance, a simpler structure, etc.

The gears are usually provided with individual lever-operated hydraulic brakes for parking and handling purposes, particularly to aid in easing the plane down the ramp.

Steel castings (higher strength) and chrome-molybdenum tubing are usually the main materials used in beaching-gear structures. Forgings are also used at highly stressed points and stainless steel at points of likely corrosion such as pins and wearing surfaces. Though weight is not a main consideration, in normal service it has proved desirable to keep it as low as practicable for convenience in handling the units.

LANDING GEARS

Water.—The obvious purpose of a landing gear is to permit the plane to take off or land from water, land, or both. A plane

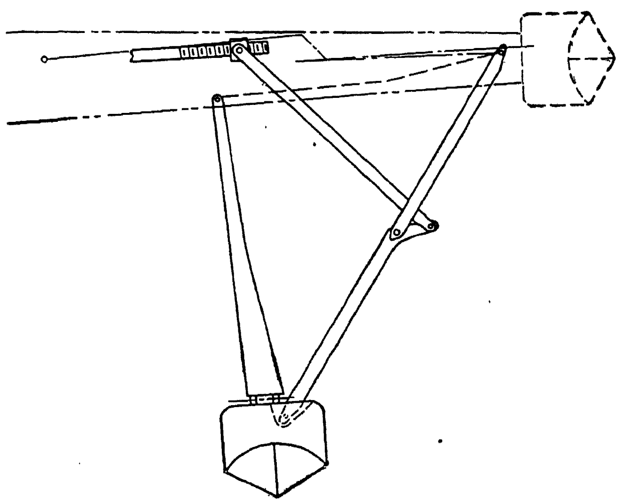


FIG. 2.—Retractable wing-tip float on PBY flying boat.

operating off water must have some combination of floats or hulls to provide static buoyancy and planing lift. The design of floats and hulls comes within the province of another engineering group, but the mechanism used in operating auxiliary retractable floats is designed by the landing-gear group.

The best-known and most successful tip float has been used on Consolidated PBY patrol planes (see Fig. 2). The float is bolted to a dural monocoque drag brace pivoted to the wing somewhat

inboard of the wing tip. Side loads are taken by V struts that fold and retract the float by means of a link fastened to a bronze trunnion operating on stainless-steel screws. The screw mechanisms are driven by means of light dural torque tubes and gearboxes from a central electric motor and manual drive. When the float is retracted, the V struts fold inside the wing, the drag panel fills the underside of the wing cutout, and the float forms the wing tip, providing some lift and giving some end-plate effect with a very large reduction in drag.

On more recent designs, where the wing aspect ratio and taper have become high, it has been necessary to retract the floats inboard, either flush with the bottom of the wing or partly retracted into the wing. This gives a hard design problem in respect to obtaining a sufficiently strong float-retracting structure without compromising wing structure too much. Examples of this type are the Consolidated Model 31 and the Martin PBM patrol planes. Some thought has been given to collapsible floats, and further work may prove this method to be feasible in cutting aerodynamic drag.

Land.—Airplanes designed to operate from the ground are equipped with various combinations of wheels and skids to take off and to land. The landing gears may be fixed or retractable and equipped with either a nose gear or tail gear.

A typical landing-gear unit consists of a pneumatic tire and tube, a wheel incorporating a high-capacity brake, a tapered tubular axle fastened to a knuckle or fork in turn attached to an oil-air type of piston shock absorber suitably connected to the airplane structure. The connection members are usually designed to fold and retract the gear into the wing, hull, or fuselage when in flight to reduce aerodynamic drag (see Fig. 3). A brief summary of the equipment and designs as used in present-day practice follows:

Tires.—Most-used types are the smooth contour (U.S. Army design) and the low pressure (commercial design). Other existing types are the streamline, high pressure, intermediate and Airwheels. Tires have been built in sizes up to 96 in. in diameter, carrying 82,000 lb. Most tires have a smooth tread and are relatively thin-walled. Inner tubes come in three types: standard, punctureproof, and dual seal. The punctureproof tube is lined with a self-sealing compound that seals around

nails or cactus spines, preventing leakage. The dual-seal tube has a fabric-reinforced inner tube that expands and sustains the tire when the outer tube is punctured.

Wheels.—Wheel types are designed and named to suit the corresponding tire styles. Most present-day landing wheels are cast magnesium alloy. Aluminum alloy is used on very small wheels and on amphibian wheels because of better corrosion resistance. Wheels are modified largely to accommodate the type of brake used.

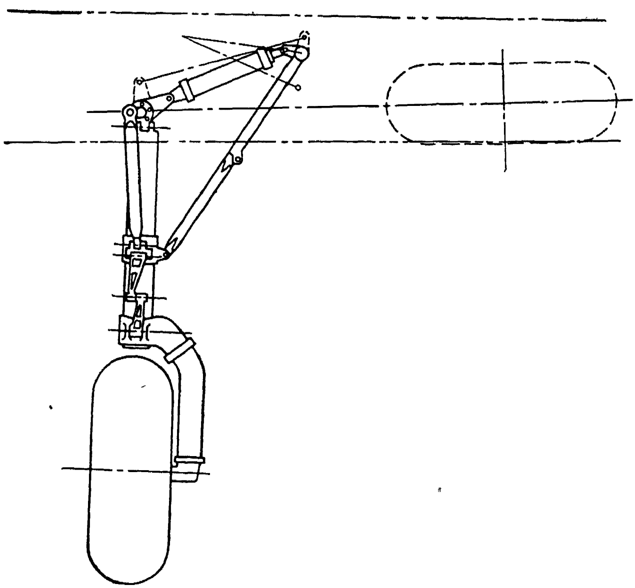


FIG. 3.—Typical main landing-gear assembly. Designed for retraction into the wing.

Brakes.—These fall into two main classes: drum and disk brakes. The drum brakes in turn are of two types: the shoe and the expander-tube brake. Disk brakes are of the multiple-metallic-disk and the single-disk type with brake lining.

All these types are made as single units or with brakes on each side of the wheel. The energy-absorption requirements of brakes have been continually increasing, with larger airplanes and higher landing speeds. All but very small brakes are hydraulically operated. Some small sizes are mechanically actuated, and a few air-operated brakes have been used. On planes up

to about 12,000 lb. weight, foot-operated master cylinders are used. Above this figure, power brakes are necessary. Brakes are usually controlled by toe or heel pedals connected to the rudder pedals. Parking is accomplished by a separate manual control.

Shock Absorbers.—Shock absorbers on all but the lightest of aircraft are of the oleopneumatic (oil-air) type. An oleopneumatic strut consists of a piston telescoping in a cylinder under load, forcing oil through either a fixed or a metered orifice that dissipates the energy of landing. A quantity of compressed air is also in the strut which returns the strut to the static position upon landing or to the extended position upon take-off. The air pressure keeps the oil forced against the lips of chevron-type rings that keep the strut sealed. Only occasional servicing with air and oil is required.

Oleopneumatic struts have an efficiency range of from 70 to 90 per cent. In some designs the struts work only as pin-ended columns and are quite light. However, on many modern planes the shock absorber serves as the main element of a cantilever structure and consequently is designed to carry bending and torsional loads. Torque is transmitted through the sliding elements by torque arms, or scissors. This method superseded the former practice of using splines, being lighter, cheaper, and less apt to induce binding. Other shock-absorber types in use are shock cord, rubber disk, metallic spring, and plain pneumatic; but these are found mainly on small craft where cost is important and requirements are not severe.

Retracting Mechanism.—The supporting structure of the landing gear is designed to fold and retract the gear into the structure chosen to house it, which may be an engine nacelle, the wing, or the fuselage. The retracting force may be supplied manually, hydraulically, or electrically. Manual retraction is normally accomplished by a hand crank and gearbox operating a torque-tube drive, which turns some type of screw mechanism that retracts the gear. This is a typical method; many different and ingenious drives have also been designed.

Manual power is sufficient only on smaller planes. A central electric or hydraulic motor may be added to the system described above as the size increases. Individual electric motors are sometimes used on each landing-gear unit.

Latest design trends have favored hydraulic systems. With few exceptions, double-acting hydraulic jacks are fastened directly to the landing gear and may be used not only to retract and lower the gear but also to actuate down and up locks, allowing considerable flexibility in design. The hydraulic pressure is applied by an engine-driven pump with a hand pump provided for stand-by.

In addition to the regular operating system an emergency lowering device should be provided that is completely independent. This may be mechanical or hydraulic. It is used only in case of failure of the normal operating means.

Landing-gear Arrangement.—The so-called "conventional" landing gear has the main wheels located slightly ahead of the center of gravity of the airplane with a tail wheel, or skid, placed near the rear end of the fuselage. This has proved fairly satisfactory, but during the last few years it has to a great extent been replaced by the *tricycle gear*. This has the main wheels placed slightly aft of the center of gravity with a nose wheel as far forward on the fuselage as is practical. The following list of the advantages and disadvantages of the tricycle gear will show why it has been generally adopted.

Advantages of the tricycle gear:

1. Inherent stability, no ground loop tendencies.
2. Permits full brake application without danger of nosing over.
3. Permits high-speed taxiing.
4. Provides better pilot visibility, because ship is in flight attitude on the ground.
5. Aids passenger comfort by the reason of small change of flight and ground angles.
6. Allows slightly faster take-offs.
7. Greatly reduces amount of pilot skill necessary for safe landings.

Disadvantages of the tricycle gear:

1. Nose gear somewhat heavier than comparable tail-gear installation.
2. Requires better brakes, because little landing energy is absorbed by air drag.
3. Difficult to install on single-engined or short-nosed planes, owing to lack of space and insufficient wheel base.

CHAPTER VIII

ELECTRICAL EQUIPMENT

Detail design of electrical installations in aircraft of today is a complex task.

Ignition System.—The ignition system is composed of one of the following: a magneto and magneto switch, a magneto with booster magneto (hand-operated), a magneto with booster magneto (starter-operated), or a magneto with booster coil (externally energized).

Lights.—Lights are all special-purpose installations.

Exterior.—The exterior lights are for the following purposes: navigation (running) lights, wing tip and tail; pair of landing lights for visibility when near the ground; various formation lights according to the requirements of the service, U.S. Army or Navy; various special lights for specific functions, such as anchor lights, recognition lights, and bomb-release lights, usually a flash type, to suit either the U.S. Army or Navy specifications.

Interior.—The interior lights of an airplane are equally specialized. *Instrument lighting* is very important for operations. There are three types, as follows: dashboard type, or reflection lighting; ring light, around instruments; fluorescent lighting, of either the radium-salts or the organic-salts type.

Compartment lighting is necessary for crew functions such as radio operation and navigation and for activities in the crew's quarters.

Equipment.—The electrical equipment (all items listed in detail specifications) consists of the following:

Engine.—Engine equipment is made up of the following items: electric propeller control for variable pitch or constant speed, Curtiss or Hamilton Standard types; engine starter (booster coil for all starters) of one of three general types, electric inertia, direct cranking, or cartridge; electrical automatic or manual electric control of cowl flaps; various shutters, operated electrically, for carburetor air-intake control, oil-cooler air flow, and inter-

cooler air flow; some primers solenoid-actuated; oil-dilution system and engine heater control sometimes electrical.

Instruments.—There are electrical instruments for many purposes. The engine instruments are of the resistance-bulb type for measuring of oil temperature, carburetor-air temperature, and free-air temperature. The selsyn synchronous types are for all above and tachometer, oil pressure, fuel pressure, oil quantity, fuel quantity, manifold pressure, position indicator, tab, landing gear, flap, etc. The autosyn type is used for and is interchangeable with the flow meters and also for the liquidometer. Exhaust-gas analyzer and thermocouple are electrically operated. These instruments vary slightly to U.S. Army or Navy specifications.

Ice Elimination.—Many electrical devices are used for ice elimination. In the propeller anti-icing system, an oil pump and oil-pump control rheostat are necessary. For the de-icers in the wing a vacuum distribution valve and engine-exhaust fan for exhaust gases are electric. In the carburetor installation the preheater, etc., and heated Pitot tube are electrically connected.

Electric Motors.—Many electric motors serve throughout the airplane. They are used for retractable landing gears, retractable floats, operation of flaps, bomb doors, bilge pumps, and turret control, either hydraulic with individual pump and motor or straight electrical drive. The vacuum pump is driven by an electric motor as well as the trim-tabs drive and engine shutters.

Miscellaneous.—Equipment in the electrical system for armament includes gun solenoids, bomb-release solenoids, and the bomb-train-release mechanism.

For heating and ventilating, various types of heater igniters, fans, and window-defrosting heaters are required. Radio and interphone sets for the radio-compartment transmission, receivers, and interphone communications are installed.

In the galley, cooking equipment must include a stove or hot plate and a coffee percolator.

Other items are miscellaneous signal lights, foghorn, flare release, spotlight, heated flying suits, and camera equipment.

Load Schedule. *Requirements.*—A load schedule must be set up in order to design an integrated system. The requirements are the determination of the most severe load condition and the corresponding determination of the power supply available.

Generators.—Power-supply generators fall under four general headings: main-engine generators of standard size and type; small special auxiliary engine-driven generators of a size and type appropriate for the load; voltage regulators of the vibrator, Silverstat, or Eclipse type; alternating-current power supply from auxiliary power plants.

Switchboard.—The electrical switchboard is composed of an ammeter, a voltmeter, the main switches, and the circuit breakers, all in plain sight and easily accessible.

Installation. *Location.*—In designing the installation of equipment one must consider carefully the location of equipment according to the specification requirements as stated in the U.S. Air Corps Handbook for Aircraft Designers, the type specifications, and the equipment specifications.

A wooden mock-up of the complete airplane always helps in the general coordination of equipment, allows a check on the convenience of equipment, and by measurement makes mock-up layouts the basis of future installation drawings.

Division into Sections.—The division of the airplane into sections by functions or according to structural considerations allows a breakdown of the equipment in the wings. The outer panel, center section, and nacelles form three major installation sections. In the fuselage, the nose section and center section, which is composed of flight deck and radio compartment, constitute three more sections. The tail section (empennage) is another.

Wire Installation.—The wire installation can be shown by sections on a wiring diagram. Here the problems are determination of simplest circuit; determination of wire sizes; types of wire; types of wire terminals; types of disconnect plugs, whether AN Standard, Cannon, or Breeze type; and optimum location of wire to avoid compass deviation.

Conduit Installation.—The conduit installation, according to a conduit diagram (isometric), involves the determination of conduit size and the location of conduit lines throughout the ship. Then a choice of conduit fittings must be made, according to Naval Aircraft factory, U.S. Air Corps, or AN Standard specifications. There are two types of conduit, solid and flexible.

Junction boxes are also located and shown on this diagram, with terminal boxes and pull boxes. The design of boxes must

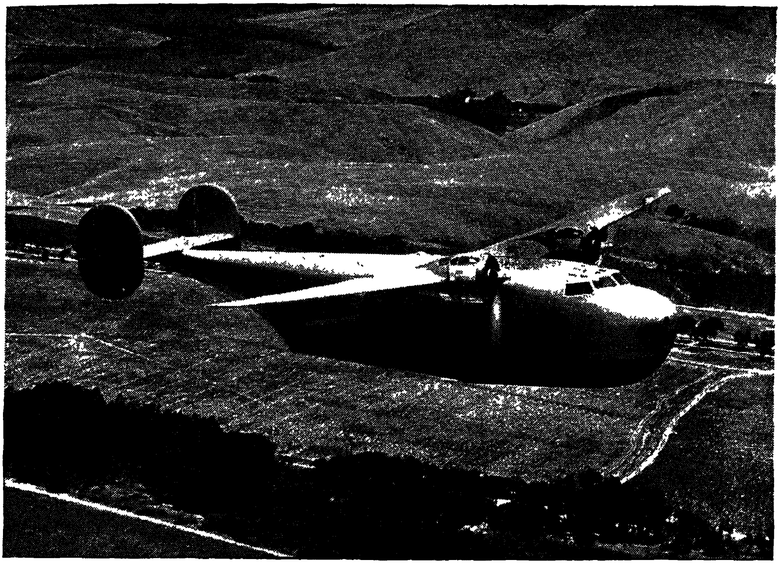
be in accordance with U.S. Air Corps or Navy specifications, also. The location of boxes with respect to accessibility is another consideration.

Radio Installation.—The command radio (G.F.) is composed of a transmitter, a receiver, and radio-operation controls. The auxiliary radio items are a loop, loop receiver, and loop control, used in navigation for "homing," directional determinations, and position. The radio loop receiver also provides bearings for navigation and allows the navigator to follow radio beacons. The antenna installation consists of a fixed antenna, a whip antenna, and a trailing antenna which is operated manually or by remote control.

The interphone installation is necessary when the crew is stationed throughout the ship. It consists of a split headset for pilots and radio operator and standard headsets for crews.

Shielding.—Shielding is required for wiring for the purpose of grounding radio interference. It may be done away with by grounding interferences at the source when an ignition harness is used

Bonding.—Bonding of all parts is necessary to prevent static discharge between components and to prevent intermittent contact. It also provides a low-resistance ground for return circuits. The methods of bonding are carefully specified by the U.S. Air Forces. Riveted structures do not require bonding, nor do bolts or clamps. Bonding braid must be placed between all adjacent moving parts. Requirements of a good bond are clean contact surfaces and a protective coating immediately after application of bond to prevent corrosion. A maximum resistance of 0.0025 ohm is required for all bonds.



Consolidated Model 31 flying boat. (*Photograph by Otto Menge.*)

CHAPTER IX

AIRCRAFT HYDRAULICS

Applications.—Hydraulic force from cylinders or motors has many applications in an airplane. For landing gears a cylinder is used for retracting; for flaps, motors or cylinders have been used. The operation of bomb doors may be by either means. Automatic pilots depend entirely upon hydraulic cylinders. The best flight-control boosters are hydraulic cylinders, as are brakes and shimmy dampeners. Gun-turret operation by hydraulic motors and jacks is very common practice. Minor applications of hydraulic systems are fuel-transfer pumps, cowl-flap operation, and gun chargers.

Systems. *Hand Pump.*—Hydraulic systems are varied, depending upon the designer's viewpoint. Hand-pump systems are of small capacity and usually for emergency operation of regular gear. They are operated by a wobble pump.

Power Driven.—Power-driven hydraulic systems are common in large planes. *Accumulator systems* involve the use of a tank under static air pressure to maintain a hydraulic pressure. They have the advantages of sustained pressure regardless of load or pump speed, greater speed of operation, greater flexibility of application, and availability of equipment. The disadvantages of accumulator systems are that they are more vulnerable to gunfire, owing to constant high pressure, and more subject to failure from continued pressure and that they require thermal-relief valves to govern the maximum pressure. Accumulators and unloading valves give trouble due to mechanical imperfections making the landing-gear latches inoperative; or the landing-gear latches may become operative unintentionally, owing to pressure rise with temperature rise.

Open-center systems have advantages not found in the other types. The open center is a completely unloaded system, less subject to failure due to fatigue. In different parts of the system, pressures are adjustable to requirements, landing-gear latches operate as intended, etc. It is less vulnerable to gunfire, and it does not require thermal-relief valves. No accumulator or unloading valve is necessary.

The disadvantages of an open-center system are that kickout pressures must be set somewhat higher than normal operating pressures and operation may not be complete if the load is abnormal. The open-center system also requires specially made valves.

Sequence Operations.—For sequence operations such as retracting, locking, and indicating in order, *restrictor systems* are necessary so that, as one cycle is completed, the increased pressure will operate another circuit. *Sequence valve systems* are also used for sequence operations, the completion of one operation opening a valve to begin the next operation.

PUMPS

Hydraulic pumps are of three general kinds, which may be the piston, gear, or vane type; *electric-driven;* and *hand pumps.*

Engine-driven Pumps.—Pumps are of either the constant-displacement or the variable-displacement type.

In the constant-displacement hydraulic system the pump continually circulates a constant volume of fluid, the pressure

depending on the setting of the pressure-regulator valve which is sensitive to rise in pressure.

In the variable-displacement system, the circulation of fluid ceases, but pressure is maintained and flow begins just as soon as demand for volume is made upon the system, evidenced by a slight drop in pressure to which the pump is sensitive.

Pumps are additionally classed into three main groups: the vane type, the gear type, and the piston type.

Vane-type Pump.—Figure 1 illustrates the simple vane-type hydraulic pump, or generator. Fluid is compressed between the blades, or vanes, as the eccentric rotor revolves. Suction is caused by the vacant volume occurring after delivery. Slight spring pressure holds the blades against the housing at low speeds, and centrifugal force takes up

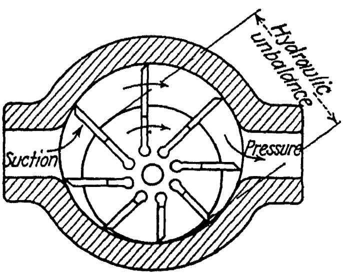


FIG. 1.—Simple vane-type hydraulic pump.

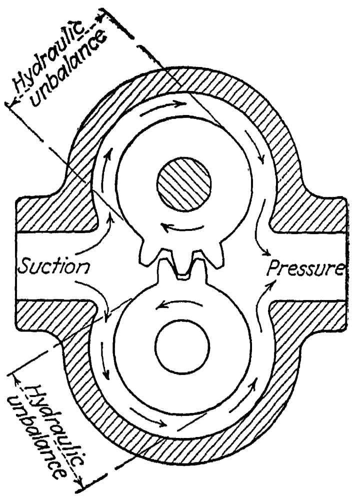


FIG. 2.—Hydraulic gear pump.

this function as rotation and pressure increase. Because it is unbalanced hydraulically, bearing loads become impracticable above moderate pressures. The vane pump may be hydraulically balanced by incorporating an additional inlet and outlet port in quadrature. The operating pressure may then be increased, but the limit is soon again reached because of buckling of the flat surfaces and high Brinelling loads on the scraping surfaces. Figure 2 illustrates a balanced-type vane pump for 1,000 lb. per sq. in. pressure.

Gear Pump.—Figure 2 shows the arrangement of the driven and idler gear and ports. Fluid is squeezed between the teeth and housing; centrifugal force supplies velocity head which is

turned to pressure head at the outlet port. The simple gear pump is unbalanced hydraulically, the unbalance extending approximately over the projected diameter of the gear as shown. Bearing loads therefore limit the operating pressure. By introducing ports in quadrature the gear pump may be given a better hydraulic balance, but leakage due to flexure of the flat areas

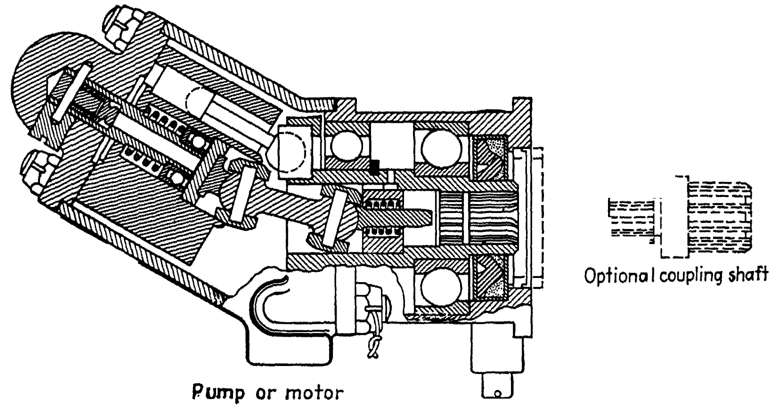


FIG. 3.—Piston-type constant-delivery pump.

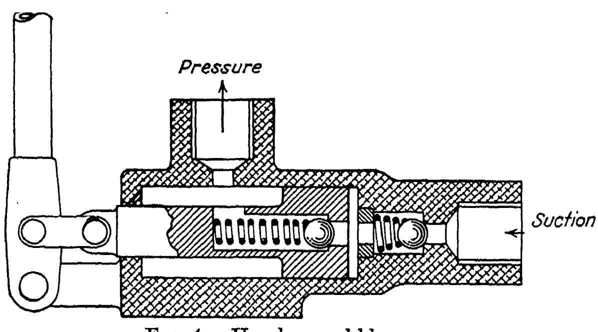


FIG. 4.—Hand or wobble pump.

limits its use for extreme pressures. A new development is a high-pressure single-stage balanced gear-type pump. Extreme pressure multistage pumps of small capacity have shown promising performance using the gear principle. The gear pump is a sort of centrifugal pump and usually turns faster than the other types.

Piston Pump.—For pressures above 2,000 lb. per sq. in. where considerable volume is required, the multicylinder piston pump

is so far the only type practical. Poppet valves become mandatory at the high pressures and rotative speeds encountered in aircraft high-output systems. Variable-displacement pumps of the piston type are now available for pressures up to 3,000 lb. per sq. in. Figures 3 and 4 show two types of piston pumps.

MISCELLANEOUS HYDRAULICS

Accumulators.—Accumulators for live-line systems are of several types. There are *piston* types and *spherical* types, both bolted and screwed. Diaphragms are located in the spherical type to separate the fluid and air so that they will not mix under pressure. The mounting position for the spherical type is oil side up. The air charge may be put in from any compressed air source.

Unloading Valves.—Various unloading valves are required throughout the system. They must be checked periodically for dirt, packing friction, and misadjustment to maintain good operation.

Actuating Cylinders.—Hydraulic actuating cylinders are simple piston and cylinder combinations. Special packing of some accepted type is used to eliminate leakage. Packing types are cups and chevrons. The materials are neoprene and other synthetic rubber compounds or graphite-impregnated composition.

Like most other moving parts the hydraulic cylinders have their faults. These are mainly leakage from faulty packing, friction from misalignment, and lack of durability in packing and piston. In hydraulic lines, swivel joints are used to avoid flexing. Compared with hoses flexing, this system is much more durable.

Hoses.—Hydraulic hoses must be impervious to the action of the fluid and capable of withstanding high pressures. Their disadvantages are that they wear with flexing and are subject to cutting and bruising.

Special Units.—Many special units are used in a hydraulic system (Fig. 5). A hydraulic unlocking jack and sequence valve are used to unlock the main landing gear so that it may be lowered or retracted (Fig. 6). Pressure switches are used to indicate limits. A special brake valve allows graduated pressure to be smoothly applied to the brakes (Fig. 7). The brake "debooster" permits low-pressure brakes to operate from a high-pressure line. The pressure regulator ensures constant pressure to all units

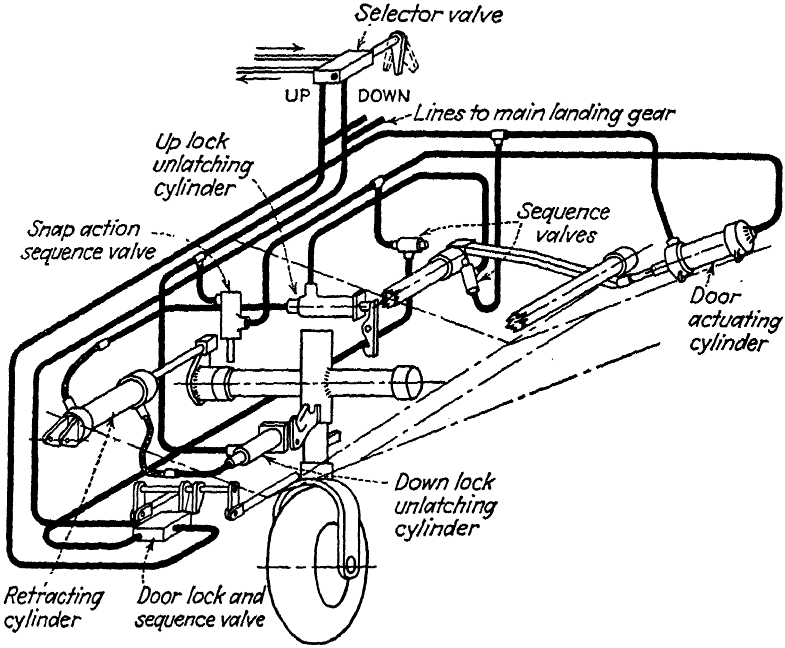


FIG. 5.—Hydraulic retracting and locking system for typical nose-landing gear.

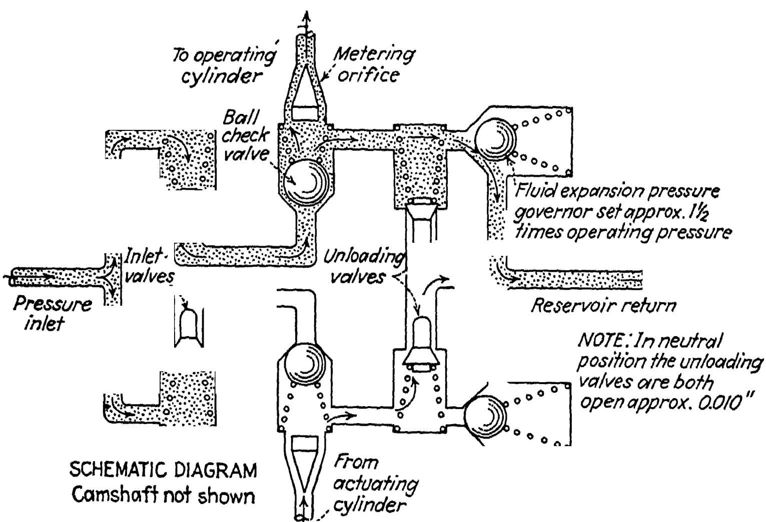


FIG. 6.—Hydraulic selector valve.

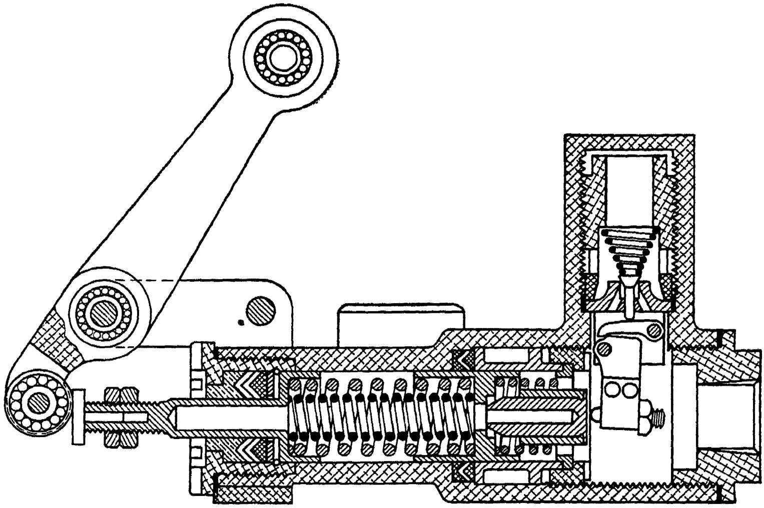


FIG. 7.—Power-brake hydraulic control valve.

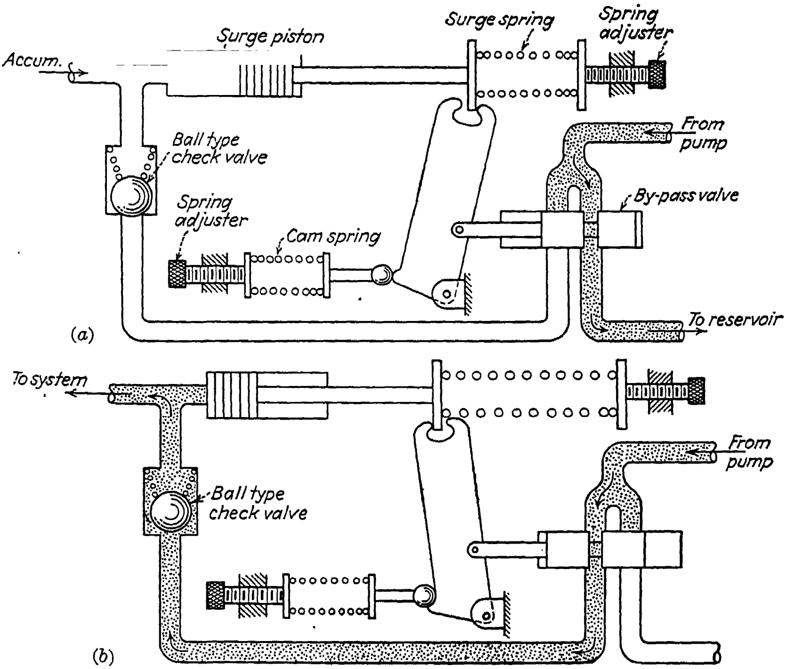


FIG. 8.—(a) Automatic pressure-regulator, pump delivery by-passed to reservoir. (b) Pump delivery under pressure to hydraulic system through automatic pressure regulator.

(Fig. 8). Test stand connections allow ground testing of all units. Various special seal couplings permit replace-

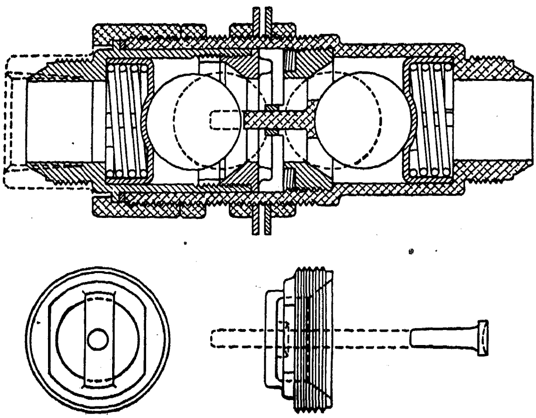


FIG. 9.—Quick-disconnect self-sealing coupling.

ment or servicing of individual units without bleeding the system (Fig. 9).

CHAPTER X

STRUCTURAL DESIGN

Function.—The function of the structures group is to design all the airplane component parts to ensure sufficient structural strength for a minimum weight, to aid in the development of a structurally efficient design, and to write stress analyses in report form showing the reason for all member sizes.

Loads.—The loads on an airplane are as follows: *Air loads in maneuvering,* which are due to the lift on the wing developed by the aerodynamic forces acting, the drag on the wing developed by the retarding aerodynamic forces, and the loads on the control surfaces due to the same action. *Air loads from gusts,* which are a function of (1) wing loading, or gross weight divided by wing area; (2) the velocity of gust which indicates the increased lift and acceleration; (3) the velocity of the airplane with which the lift varies to the second power; and (4) the slope of the lift curve which is the rate of change of lift. *Inertia loads,* which are due to accelerations in flight and landing causing additional stress over that produced by steady loads.

Load Factors.—Load factors are ratios of the applied loads to the airplane weight and, being dimensionless, are very useful in calculations.

Loads may be broken down into two major kinds, as follows: *concentrated forces* which act at a point and require heavy local structure; and *distributed forces* which act over an area and require only a stiff structure. The latter are uniformly distributed loads or forces and are varying loads.

Forces.—Forces may be considered as *vector quantities* since they have both magnitude and direction. Both magnitude and direction must be known to determine their effect. Forces that act through a common point may be combined to give a *resultant,* by means of the parallelogram of forces. The resultant force may then be used as the applied load.

$$\text{Resultant} = \sqrt{F_1 + F_2 + 2F_1F_2 \cos \theta - \theta}$$

where θ is the angle between F_1 and F_2.

Loads may, conversely, be resolved into their components along the X and Y axes, where analysis of the structure so requires. Force produces *moments* about a line perpendicular to the plane of the force that are equal to the force times the perpendicular distance between the force and the line. Moments are useful in bending analysis. Forces that are in equilibrium acting at a point have zero X components and zero Y components and produce zero moments. Forces that pull axially on a member produce *tension*. Forces that push axially on a member produce *compression*. Forces in a plane that are in equilibrium have zero resultant X components, zero resultant Y components, and zero moments about any point in the plane; or

$$\Sigma X = 0, \qquad \Sigma Y = 0, \qquad \Sigma M = 0$$

where Σ = "summation of."

Trusses.—Trusses are structures that carry only axial loads in their members. They may be analyzed by the method of joints and by the method of sections.

Stress.—A stress is a load divided by an area, giving stress in pounds per square inch. Stress causes strain, which is elongation per unit length in inches per inch. Stress divided by strain is constant up to the yield point and is called the *modulus of elasticity*, or the slope of the stress-strain curve. Stress at failure is called *ultimate stress* and is an aircraft-design criterion.

Truss members that have tension loads may be designed to carry the ultimate stress. Truss members that have compression loads tend to buckle laterally, before the ultimate stress is reached, and are called *columns*. Columns are designed by column equations which have graded constants depending upon the fixity of the column ends.

Beams.—Beams are members that are loaded normal to their axis and carry the load by bending. Beams have some fibers in compression and some fibers in tension and are also subjected to shear, which is the tendency of one fiber to slip over the adjacent fiber. The fibers in compression are on the side at which the load is applied.

Axial stresses in beams are proportional to the distance from the c.g. of the cross section, known as the *neutral axis* of the section. These stresses are determined from the moment equation

$$f_b = \frac{MY}{I}$$

where M is the bending moment, which is the moment of all the forces to one side of the section in question, about the section in question; Y is the distance from the c.g. of the cross section to the fiber in question; and I is the moment of inertia of the cross section. Axial stresses in beams are maximum at the outermost fiber of the section.

Shear stresses in a beam are maximum at the c.g. of the cross section, or along the neutral axis.

Torsion.—Torsion is the twisting effect of a moment that is in a plane perpendicular to the axis of the member. Torsional stresses in round members may be obtained from the torsion equation

$$f_s = \frac{TR}{I_p}$$

where T is the torsional moment, R is the radius, I_p is the polar moment of inertia, and f_s is the torsional stress.

Joints.—Joints in structural members may be riveted, bolted, or welded.

The strength of riveted and bolted joints depends on the size and composition of the rivet, or bolt, that carries the load by shear and on the thickness and composition of the material being riveted or bolted, that carries the load from the rivet or bolt by bearing.

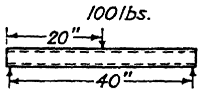
The shear stress on a bolt or rivet equals the load divided by the rivet or bolt area.

The bearing stress on the sheet equals the load divided by the thickness, times the rivet or bolt diameter, giving a stress in pounds per square inch.

The strength of a welded joint depends on the length of weld in inches, on the gauge and composition of the material being welded, and on whether the material is welded before or after heat-treatment. If heat-treated after welding, greater strength will be realized.

Airplane structures are broken down into beams, trusses, or torsion-carrying members and are analyzed and designed as idealized structures in these categories.

Problems.

1. 

A beam of 1 by 0.065 in. tubing has a moment of inertia of 0.02097 in.[4] What is the maximum bending stress?

Ans. The reactions are equal and are 50 lb. each. See figure. Maximum bending moment would be at the 100-lb. force and equals $50 \times 20 = 1{,}000$ in.-lb.

$$f_b = \frac{MY}{I}$$

$$\therefore f_{b\,\max} = \frac{1{,}000 \times 0.5}{0.02097} = 23{,}900 \text{ lb./sq. in.}$$

2. How much will a bar 1 sq. in. in area and 10 in. long elongate owing to a tension load of 50,000 lb. if the modulus of elasticity is 29,000,000 lb. per sq. in.?

Ans. $\text{Stress} = \frac{P}{A} = \frac{50{,}000}{1} = 50{,}000$ lb./sq. in.

$$\text{Strain} = \frac{\text{stress}}{E} = \frac{50{,}000}{29{,}000{,}000} = 0.00172 \text{ in./in.}$$

Elongation $= 0.00172 \times 10 = 0.0172$ in.

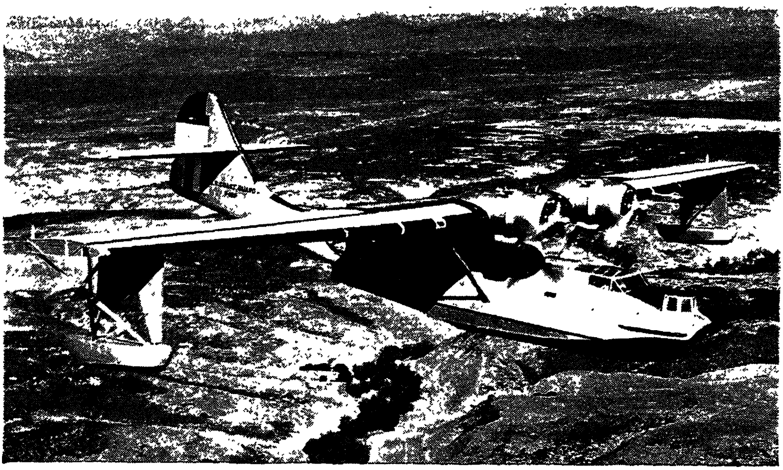
3. How many $\frac{3}{16}$-in. 17ST rivets per inch would be necessary to splice an 0.040 Alclad sheet to an 0.064 Alclad sheet if the tensile stress in the 0.040 sheet is 25,000 lb. per sq. in.?

Allowable shear on a $\frac{3}{16}$-in. 17ST rivet $= 828$ lb.
Allowable bearing of a $\frac{3}{16}$-in. 17ST rivet on 0.040 Alclad $= 553$ lb.
Allowable bearing of a $\frac{3}{16}$-in. 17ST rivet on 0.064 Alclad $= 984$ lb.

Ans. Load per inch to be spliced equals $0.040 \times 1 \times 25{,}000$ which equals 1,000 lb. The rivets are critical in bearing on the 0.040 sheet; therefore,

$$\frac{1{,}000}{553} = 1.8$$

or 2 rivets per inch will be required.



United States Coast Guard patrol plane built by Consolidated Aircraft Corporation. (*Official Photograph, U.S. Navy*)

CHAPTER XI

MODERN AIRCRAFT MATERIALS

Material and Drawing Release Procedure.—The drawing goes from the draftsman to the materials engineer and group leader for approval when completed. Each group has a materials engineer who checks drawings to see that the materials called for are standard and available. The materials engineer often notifies the materials group well in advance of release of the drawing by a written order to order the materials and purchased parts called for on the drawing. This is necessary in view of the fact that deliveries are often delayed.

Drawings are then sent to the structures group for approval. They may shuttle back and forth between the design and structures groups many times before being "O.K.'d," owing to changes suggested by the structures group.

After the group leader's "O.K.," the drawing is sent to the project engineer for approval, then to the material and release group.

The drawing goes first to the bill of materials section of the materials group. Here all drawings from all groups are recorded. Drawings intended for U.S. Navy inspection are held aside for Navy approval, after which they enter the bill of materials system in the usual way. A new drawing is handled as follows:

The bill of material on the drawing is checked and recorded on a special drawing bill-of-material form. A check is made for correct gauges and maximum sizes of sheet-metal stock, correct specifications (U.S. Army or Navy, Federal or AN), and proper heat-treated conditions. Conditions of various materials depend on shop practices in making parts. All drop-hammer, hydropress parts, and strip stock for drawn or rolled sections made from Alclad require 24SO material. For parts made from flat sheet or having large-bend radii, 24ST material should be used. A check is also made to see that material sizes called for do not exceed maximum sheet-stock sizes as set down by the manufacturer. In the case of castings, the bill-of-materials section checks to see that these are properly called out on the drawing in accordance with current practice as defined by the drafting room manual. Forgings, which constitute a major procurement bottleneck, because of their distant delivery dates, must be promptly and correctly released. Where it is anticipated that these parts will be needed before delivery can be obtained, the bill-of-materials section must see to it that proper substitutes are made by the design groups. In short, every dash number, standard part, or purchase part called for by the draftsman must be thoroughly checked by the bill-of-materials section.

At this time the design group's "order to release" is checked to see that the drawings are released for the proper models. When this has been done, the drawing is sent ahead to the release section.

The materials group tabulates all material and arranges for quantity purchases. Check is made against preliminary orders that were placed prior to the release of the drawings of the airplane. Preliminary material orders are issued because it is necessary to have material on hand so that parts can be fabricated upon release of the drawings. Additional orders are placed, if necessary, when it becomes evident from the drawings that shortages in certain materials have occurred.

The bill of material that has been drawn up from the bill of material on the original tracing is then routed to the various sections of the materials and release group. It should be noted at this point that the various types of materials which go into the plane are handled by specialists. For instance, purchase parts such as motors, propellers, and electrical equipment are handled by one group, another group will handle fittings, AN parts, and company standard parts. The bill of material as drawn up by the bill-of-materials section will indicate to these groups exactly how many of each part are to be ordered for each ship. The group in charge of what are termed "miscellaneous" materials, such as Plexiglas, soundproofing materials, and neoprene sheet, will get their requirements from the bill of material in much the same manner, except that, in their case, they will have to detail and then at certain intervals summarize the amounts of the various materials called for on many different drawing bills of material.

Still another section of the materials and release group is the raw-stock section. This group releases all the sheet metal, extruded and drawn sections, forgings and castings, and many different types of tubing that go into the plane. Drawn sections, being often made in the plant, must be broken down, not only into lengths of sections required, but also into amounts of raw (strip) stock to make these sections.

When the various groups have taken all the necessary information from the bill of material and transferred this to their own tabulation sheets, "ditto" copies of the originals are then sent to the purchasing department for ordering if necessary.

The release section, when it receives the drawing from the bill-of-materials section, checks the drawing for the proper number of company parts called for on the drawing and also checks the next assemblies. A release sheet is then written on special "ditto" forms, showing the drawing number, title, sizes, and requirements for one or more next assemblies. The release sheet also indicates the model and the number of airplanes on which the part is used. "Ditto" copies of these releases are then made up and are sent to the design, planning, tool-design, engineering-weights, purchasing, and loft departments.

The drawing is then sent to the blueprint department, where prints are made and distributed to the planning, tool-design,

loft, and inspection departments, not forgetting, of course, two copies that are kept in the engineering files.

It is well to keep in mind that one of the important functions of the release group is to coordinate the work of the various engineering groups with the shop, planning, and purchasing departments.

When one of the engineering design groups wishes to change the design or the method of making a part that is already in production, and to eliminate as much as possible the scrapping and reworking of certain parts, a stop-order form is issued by the design group. The release group issues a stop order by memorandum to the planning and tool-design and loft departments, stopping all shopwork on that particular part until the changed design is sent through. It is very often necessary for the release group to follow up the original stop order, in order to expedite the re-release or cancellation of a stop part.

When a drawing change is made, the drawing goes through the bill-of-materials section in the same way as a new drawing, except that the bill of materials originally drawn up for the new drawing is taken out of the files, the necessary changes are made, and it is then sent through the material and release group system, as before. When a drawing is canceled, the raw stock and purchase parts called out on the drawing must also be canceled. This means that the bill of material originally drawn up by the bill-of-materials section must also be canceled and sent through the group so that the purchasing department may also cancel its orders for materials originally called out on the drawing. The release section at the same time cancels its releases, and cancellation notices are sent to the planning, tool-design, and other departments who were originally informed of the release of the drawing.

The material and release group is also responsible for compiling a complete bill of material for the Army or Navy, depending on the model, and must show all materials and purchasing parts used per airplane for each contract.

Aluminum and Its Alloys.—At the present time, aluminum alloys are used almost exclusively in the construction of aircraft. Aside from fittings carrying highly concentrated loads or other parts subject to severe wear or corrosion for which special aircraft steels are used, the general structure of the airplane is fabricated

of aluminum alloys. The reason for the extensive use of aluminum is primarily its light weight, high strength, ease of fabrication, and availability in many forms. Its weight is approximately one-third that of steel. It is available in many tempers and forms, and consequently the proper type of aluminum may be procured for practically any application.

Bauxite, an ore, is at the present time the principal source of aluminum, although aluminum in various chemical forms is one of the most plentiful metals to be found in the earth's crust. The principal difficulty, however, has been in separating it from the various clays, soils, and rocks in which it is found. Up to now, this has been commercially practicable only in the case of bauxite and, very recently, alunite.

Bauxite is largely aluminum oxide mixed with impurities. By a chemical process, the pure aluminum oxide, alumina, is obtained. Then, by an electrolytic process, pure metallic aluminum is obtained from the oxide. The aluminum is then cast into pig form. These pigs are remelted, and by adding other elements during the remelting operations many different alloys are obtained and recast in ingots.

Many forms of aluminum are made from the ingots by rolling, drawing, extruding, or forging. Certain of the alloys have characteristics that make them especially desirable for castings.

Nomenclature.—Aluminum alloys are obtainable in either cast or wrought forms. They may be further classed as nonheat-treatable and heat-treatable alloys.

The chemical composition of the alloys is indicated by the alloy number. Wrought alloys are distinguished from cast alloys by the letter S following this number. For example, 3S, 14S, 17S, 24S, 52S, and 53S are all wrought alloys, differing in physical properties and chemical composition.

The casting alloys most commonly used in aircraft are as follows:

356T6, 195T4, 220T4 (for sand castings).
13 (for die castings).
356T6 (for permanent mold castings).

The nonheat-treatable alloys, or alloys that must be strain-hardened in order to obtain the different tempers, are designated as follows: 52S-$\frac{1}{4}$H, 52S-$\frac{1}{2}$H, 52S-$\frac{3}{4}$H, 52S-H. These tempers

are obtained by cold-working the alloy. The H stands for "hard," and the relative hardnesses are indicated by the fractions. In the annealed, or soft, state, the letter S is followed by an O, for example, 52SO.

Wrought alloys that have been hardened by heat-treatment have a letter T following the S, as 14ST, 17ST, 24ST, 53ST. The same alloys in the soft, or annealed, condition are designated by the letter O following the S, as 17SO, 24SO, 53SO.

Alloys in the heat-treated condition may be strain-hardened to improve their physical properties. This strain-hardened condition is indicated by the insertion of the letter R between the S and T, for example, 24SRT.

Broadly speaking, it may be said that all wrought aluminum alloys fall into two classes, *strain-hardened* or *heat-treatable.* In the first, the physical properties may be improved only by cold working. In the second, the properties are improved by heat-treatment. The strain-hardened alloys do not respond to heat-treatment, except that they may be annealed, or softened, thereby. As it is possible to obtain greater strength from the heat-treatable alloys than from those that are strain-hardened, the former are used for structural purposes in aircraft in preference to the strain-hardened alloys.

Alclad.—The all-metal airplane of today is constructed primarily and predominantly of what is known as *Alclad.* This is aluminum-alloy sheet having a surface layer—very thin—of aluminum of high purity. The pure aluminum, being exceptionally corrosion-resistant, protects the alloys that it covers. Furthermore, by electrolytic action, it protects the metal from corrosive attack through scratches and through the sheared edges of the metal parts. The aluminum coating is put on the alloy core by a rolling process that makes it an integral part of the metal. 17ST rivets, which are commonly used in the riveting of Alclad sheet, are also protected by the electrolytic effect of the pure aluminum coating on the sheet metal. One great advantage of Alclad is that it retains most of its initial strength over a period of years, whereas the plain, uncoated alloys may lose a great deal of their strength and nearly all their ductility after only a few years of severe service.

Aluminum-alloy Extrusions.—Aluminum-alloy extrusions are made when special structural shapes are required. The most

common shapes are channels, angles, T sections, and Z sections. The process of making extrusions may be compared with that of squeezing tooth paste out of a tube. The paste always assumes the shape of the opening through which it is forced. Similarly, in the extrusion process, a cylinder of aluminum alloy that has been heated to a temperature of 750 to 850°F. is forced by a hydraulic ram through an aperture in a die. The aperture has the exact shape of the cross section of the finished extrusion. After extruding, the material is straightened by stretching. Practically all the extruded sections used in aircraft are of 24ST, for at the present time this is the strongest alloy obtainable for this purpose.

When an extruded section having special structural properties is desired and such a section is not available, a drawing is made of the section and sent to the manufacturer, who makes the die according to the drawing and is then able to produce the extrusion in quantity.

Aluminum-alloy Forgings.—Aluminum-alloy forgings also find considerable use in aircraft construction. Most of the high-strength fittings throughout the airplane are forged, although, where unusually high strength is required, steel is used. In making a forging, the metal is heated to the proper temperature and then hammered or drop-forged to shape. Dies having the desired shape are used, except that these must have a 7-deg. draft on all vertical surfaces, so that the dies may come apart properly and the part may be removed without too much difficulty.

It is interesting to note that it requires more power to make an aluminum forging than a steel forging. This is due to the fact that the aluminum alloy must not be heated to too high a temperature, for otherwise it becomes crumbly. Hence, at the proper forging temperature, the metal is not hot enough to flow easily, and thus tremendous pressures are necessary in order to form it.

The forging alloy most commonly used in airplanes is 14ST. This alloy has the highest mechanical properties of all the forging alloys and is used wherever high strength and good corrosion resistance are required. Another forging alloy used is A51ST. This alloy forges much more easily than 14ST and is used for large, intricate parts where 14ST cannot be used and

where high strength is not of primary importance. Aluminum-alloy propeller-blade forgings are made from 25ST.

Aluminum-alloy Castings.—Aluminum-alloy castings are used throughout the airplane where unusual strength is not of paramount importance. As is the case with all castings, their mechanical properties and shock resistance are not so good as those obtainable with wrought alloys. However, with certain precautions and with intelligent design, they serve many useful purposes in the airplane. Castings are particularly useful where a part is so complicated that it would be difficult and expensive to machine it from bar stock.

There are many different casting alloys available, each with its own characteristics and properties. The use to which the cast part is to be put must be the criterion for its selection. The properties desired may be any of the following: corrosion resistance, ease of casting, low cost, strength, shock resistance, etc.

The type of casting must be considered also. Is it to be a sand casting, a permanent-mold casting, or a die casting? Each type determines the alloy to be used. Most aircraft manufacturers have more or less established standards on the types of casting alloys that they believe best suited to their requirements in making one or another of the aforementioned types of castings.

Aluminum-alloy castings are poured not only in sand molds but also in permanent metal molds. Also, some of the alloys are particularly suited to casting in pressure die-casting machines.

The type of casting process to be chosen depends on a number of considerations. Because of the cost of a permanent-mold or die-casting die in comparison with that of pattern equipment for sand casting, these processes are practical only where a large number of identical castings are required. The minimum number that will justify the production of a metal mold or die varies greatly with the nature of the casting.

The surfaces of castings produced in metal molds are usually smoother and the dimensional tolerances closer than those of sand castings. Because of this, the saving in machining or finishing costs may make the permanent mold or die casting more economical than the sand casting in cases where the number required would not otherwise justify the mold or die. For large or intricate cored castings, sand molds are necessary.

Casting Alloys.—Certain casting alloys that are susceptible of heat-treatment have come into almost universal use because of their superior mechanical properties. Two of these bear the Alcoa numbers 195 and 356. The former has a long record of good performance in a number of varied uses. It contains about 4 per cent copper and has good strength and maximum shock resistance when used in the T4 condition. The letter T after the alloy number indicates that it is heat-treated and the number following indicates the particular treatment to which it has been subjected. Thus, we have 195-T4 and 195-T6 which have quite different physical properties. Alloy No. 195-T4 is generally used in preference to alloy No. 195-T6 because the latter, though somewhat stronger, has less elongation and shock resistance.

Where the casting is complicated, alloy No. 356-T4 or 356-T6 is usually substituted for 195-T4. This alloy contains silicon and a small amount of magnesium. It has excellent casting qualities and resistance to corrosion. One of the significant characteristics of the two above-named alloys is that, on aging at room temperature for several months, the mechanical properties of the alloys in the T4 condition approach those of the T6 condition, after which there is no appreciable change.

Another alloy, Alcoa No. 220-T4, produces castings having the highest combination of tensile and yield strengths, elongation, and impact resistance of all the aluminum casting alloys. This alloy also has excellent machining qualities. 220-T4 shows effects of room-temperature aging similar to those noted for 195-T and 356-T4.

Alcoa No. 43, which contains 5 per cent silicon, is a well-known heat-treated alloy that is occasionally used because of its excellent casting qualities and resistance to attack in salt-laden atmospheres. It is fairly ductile and shock resistant, but its tensile strength is considerably less than that of the heat-treated alloys.

For permanent mold castings, alloy No. 356-T6 is generally used because of its excellent casting qualities as noted above. It is one of the characteristics of alloys used in making permanent-mold castings that they have better corrosion resistance and physical properties than if cast in sand. This is due to the fact that the molten metal is more quickly chilled as it comes in contact with the metal mold, this chilling resulting in more

rapid solidification and a finer grain. Finer grain makes permanent-mold castings more susceptible to heat-treating and improves their corrosion resistance and physical properties.

For die castings, Alcoa alloy No. 13 is used because of its excellent casting properties and good corrosion resistance, although alloy No. 85 presents a slightly better combination of strength and ductility.

Referring back to Chap. VI on Hull Design, it will be recalled that the design of the hull is made a more difficult problem by two conditions—water tightness and corrosion resistance. The latter was acknowledged to be the more difficult problem of the two, especially in designing hulls of seaplanes which operate in salt water. Corrosion, it was explained, is controlled by choice of finish and material.

To start with, we know that Alclad is by far the best aluminum-alloy sheet stock available, from the standpoint of corrosion resistance and structural strength. Therefore, we find it used for practically all the outside covering of the airplane, with the exception of corrosion- and heat-resisting steel sheet used in the nacelles and around other parts that must withstand a great deal of heat.

Reviewing briefly certain of the major structural members of the hull, we find that the bulkheads are fabricated for the most part from 24SO Alclad sheet formed to the proper contour on the hydropress and subsequently heat-treated to the ST, or hardened, condition. It should be kept in mind that every part which goes into the airplane must be in the ST condition.

All the Z sections that go into the hull are drawn from 24SO Alclad strip on the drawbench and are subsequently heat-treated and stretched 3½ per cent to the RT condition. The 3½ per cent stretch is a form of work hardening that is done to impart greater structural strength to the stringers. An aluminum-alloy extrusion specially designed for the purpose forms one of the main structural parts of the keel. The bottom plating of the hull is formed of heavy-gauge Alclad and is attached to stringers which run parallel to the center line of the ship. Forged aluminum-alloy clips are used to attach bottom stringers to the various bulkheads.

Steel.—There is one alloy steel that has been adopted almost exclusively for use in aircraft construction. This is chrome-

molybdenum, familiarly known as "chrome-moly," steel, which bears the S.A.E. number X4130. The universal use of this steel is due to its excellent welding characteristics, its ease of forming, its response to heat-treatment, and its availability in practically every form.

A typical welded assembly made of chrome-moly steel is the engine mount which is made for the most part of heavy chrome-moly steel tubing. All fittings in the airplane that must withstand unusually high stresses are manufactured either from chrome-moly bar or chrome-moly forgings. Parts subjected to very high loads are sometimes heat-treated to a tensile strength of 175,000 to 200,000 lb. per sq. in. Heat-treated parts made of chrome-moly steel cannot be welded without destroying the heat-treatment. Welding reduces the strength of the normalized metal in the region adjacent to the weld that was heated to a temperature just below the critical range of the steel. It is therefore desirable to normalize all welded parts after fabrication to regain the loss in strength and to relieve the internal stresses set up by welding.

Normalizing is a form of annealing in which the steel is heated above the critical point and then cooled in still air. Because of the more rapid quenching obtained by this method, the steel is harder and stronger than annealed metal. This heat-treatment also relieves the stresses and makes the steel more uniform in the same manner as annealing; but, at the same time, it improves the physical properties of the steel. It should be noted at this point that chrome-moly steel sheet is usually procured from the manufacturer in the annealed state, whereas chrome-moly steel tubing is procured in the normalized condition.

Corrosion-resisting steels, better known as "stainless steels," are also used in the airplane for certain specialized purposes. These bear the S.A.E. number 3140 and are sometimes termed "18-8" steels, meaning those steels containing about 18 per cent chrome and about 8 per cent nickel. One of the characteristics of the stainless steels is that they are austenitic. In this state the constituents are in solid solution and the steel is nonmagnetic. This nonmagnetic property is important where it is necessary to use steel parts in the pilot's enclosure where there are compasses and other instruments that might be affected by steel having magnetic properties. Of course, it must not be forgotten

that the strongest reason for its use is that it is highly resistant to corrosion and therefore is generally used where this characteristic is an important factor.

Stabilized 18-8 stainless steel, otherwise known as corrosion- and heat-resisting steel, is used around the motors for exhaust collectors, exhaust shrouds, and exhaust stacks, all of which are subjected to extremely high temperatures, which would soon break down ordinary 18-8 stainless steel. This special type of 18-8 steel contains stabilizing elements such as titanium, columbium, or molybdenum, which prevent intergranular corrosion of the stainless steel. Stabilized stainless steels may also be welded, those for this purpose containing titanium. It must be kept in mind that the above-mentioned stainless steels are not heat-treatable, although they may be annealed to relieve stresses caused by forming. They may have their strength increased only by cold working and not by heat-treatment. The structural stainless steels are obtainable only in tempers that depend on the amount of cold work done on them. These tempers are called one-fourth hard, one-half hard, three-fourths hard, and hard. Annealed material is also available but is not often used.

Magnesium Alloys.—Magnesium is the lightest metal used in aircraft construction. Pure magnesium weighs only 65 per cent as much as aluminum. In the pure state, magnesium is fairly soft and not particularly suited to structural uses; but when alloyed with other metals such as aluminum, manganese, zinc, copper, tin, and cadmium, it forms a number of structurally useful alloys. These are available in practically all forms.

The main drawback to the general use of magnesium alloys is that they have poor corrosion resistance and are difficult to bend or form. Consequently, they are used principally in the form of castings, forgings, or extrusions. Their main use is in the form of castings for brackets and other small, lightly-stressed parts. These are usually either sand-cast or die-cast. The alloy most generally used is called "Dowmetal H." This particular alloy has better corrosion-resisting characteristics than most of the other magnesium alloys and is fairly strong, being susceptible of heat-treatment up to as high as 37,000 lb. per sq. in. Dowmetal M is used mostly for die castings.

Other Metals and Their Uses.—*Manganese bronze* in the form of rod is used to a considerable extent in the fabrication of bush-

ings, spacers, and bearings. It may be sand-cast, and this is very often done to form what is known as "cored" tubing, which is used for bushings of large diameters. It is exceptionally strong and tough and corrosion resistant.

Phosphor bronze is used for the fabrication of bolts, electric contacts, and small, flat springs. It is very strong and has an ultimate tensile strength in rod form of 80,000 lb. When cast, it is used for bearings, bushings, and gears. It is very resistant to corrosion by salt water.

Aluminum bronze has greater corrosion resistance than manganese bronze and has very good bearing qualities. When cast, it is often used for gears, valve seats, and bearings. It has great strength and resistance to fatigue and shock. It has an ultimate tensile strength of 80,000 lb.

Super-manganese bronze, which is obtained in the form of cast rods and cored tubing, is used for large, highly stressed bushings and bearings.

Miscellaneous Materials.—In addition to the various metals just mentioned, there are other materials that play an important part in the finished airplane. For procurement purposes, these fall into the class called "miscellaneous materials." The following are some of the more important:

Asbestos in various forms is used as insulation for power-plant ducts, as chafing strip, and as packing.

The uses for *carpet* are, of course, self-evident.

Various types of *cement* are used throughout the airplane for sealing weather stripping, rubber and neoprene tubing, etc.

Canvas duck is used for weather protection on various parts of the exterior of the plane when not in service. It is also used inside the plane for curtains, stowage, and covers.

Felt is used for soundproofing and vibration damping principally.

Lead sheet is used for counterbalancing ailerons, as was pointed out in Chap. III on Control-surface Design.

Brake linings are, of course, used in the landing gear of landplanes.

Neoprene sheet of various thicknesses and hardnesses is used throughout the airplane for sealing and antivibrational purposes.

Plexiglas is almost universally used for windows, cockpit enclosures, gun turrets, and landing-light covers. It is supplied

in various thicknesses. Because it is thermoplastic, it may be easily formed to practically any contour.

Rubber also finds wide uses on the airplane for de-icer boots, flexible hose, upholstery padding (sponge rubber), and seals.

Soundproofing materials include kapok batting, quilted cotton, felt, and various other sound- and vibration-absorbing materials.

A high-grade *cotton fabric* is used for covering ailerons, tabs, and elevators.

Plywood is used for various types of flooring in the airplane.

CHAPTER XII

WEIGHT ENGINEERING

Influence of Weight.—The effect of weight on the following elements of performance of aircraft is of primary importance. The take-off distance and time must be kept to a minimum. A maximum rate of climb is also desired for most types, and maximum range and ceiling are equally desirable. For all types, minimum landing speed is a most important safety consideration. The effect of weight on the cost of manufacture is reflected in pounds of material saved. Also, the effect on the revenue of the operating company will be inversely proportional to the gross weight of the airplane.

Center-of-gravity Location.—The influence of c.g. location on the airplane affects controllability, stability, and hydronomic characteristics (in the flying boat). The c.g. must be carefully located for balance. The importance of weight and balance engineering in airplane design is demonstrated in the preliminary weight and balance estimate during preliminary design and later in the weight and balance control of the airplane while being finally designed in order to maintain the required c.g. location.

Preliminary Weight Estimate.—The functions of the engineering weight group in an aircraft manufacturing organization are preparation of the preliminary weight estimate which shows an over-all weight analysis including useful-load estimate; weight-empty estimate; government-furnished-equipment weight estimate; contractor-furnished-equipment weight estimate; breakdown of the wing weight by Drigg's formula, by Upson's formula, or by modification of Drigg's formula; breakdowns of the tail-group structure, fuselage or hull, landing gear, and nacelles; and the remainder of contractor-furnished items.

Center-of-gravity Estimate.—Next, these weights must be compiled, and by use of the moment equation the c.g. estimate is made. This is done by use of the *principle of balance* and the calculation run through.

The process of *balance calculation* is as follows:

The weight-empty balance consists of three estimates, the wing c.g. determination, the fuselage c.g. determination, and the remainder of weight-empty-c.g. determination. The useful-load and gross-weight balance is next made.

Then *relocation* of the following items to modify c.g. in percentage m.a.c. for proper stability and control in flight is made: engine, equipment, and wing, all of which can be moved forward or aft to put the airplane c.g. in the optimum position.

Weight Control of Weight Empty.—Weight control of the weight empty of the airplane is followed throughout the design by division of the preliminary weight estimate into many small unit weights, resulting in a summary termed a "bogey." Next the calculation is made of the weight of small units, as originally designed, followed by the redesign of these, if possible, in case of overweight. The maintenance of running summary of calculated weights and reduction of "bogey" weights of items not released to shop, if the net total of calculated weights of items released exceeds the "bogey," keeps the design c.g. in place.

The determination in the shop of actual unit weights acts as a design check. Further reduction in "bogey" weights of unreleased items is required if, upon completion, the net total of the actual weights exceeds the net total calculated weight. An attempt is made to limit weight increases due to changes during the flight-test period so that the c.g. and gross weight will not vary.

The importance of the proper division of a preliminary weight estimate in establishing a "bogey" must be stressed. There is no use in trying to "fool yourself." A bookkeeping system for maintaining necessary records of weight and balance is essential.

Balance Control.—Balance control, also, must be maintained by the system outlined above.

Actual Weight of Completed Airplane.—The actual weight of the completed airplane must be found by some prearranged weighing procedure, setting forth the attitudes of the airplane during weighing and all the data required, such as scale readings in pounds and measurements for moment calculations. The computations consist of a determination of the horizontal c.g. and the vertical c.g.

Loading Calculations.—The airplane loading calculations for actual maintenance of c.g. involve *calculation of the required ballast*

for the specified weight and of *c.g. location* by use of moment-arm datum lines normally used or by simplified methods using a datum line through weight-empty c.g. The *calculation of relocation* of *cargo, ballast,* or *equipment* to modify the c.g. by a specified amount when the gross weight is held constant is sometimes necessary for unusual or special flight conditions.

Conclusion.—Many weight-engineering problems result from accelerated production because of reduction in the number of standard sizes of material available and less time available for the study of the lightest types of detail construction. Moreover, production methods vs. slower methods mean weight "losses" sometimes. The present trend toward increased armament requirements, resulting in aft c.g. movement, makes the job all the more difficult.

CHAPTER XIII

ENGINEERING CONTRACT ADMINISTRATION

Procedure. *Preliminary Proposal.*—For placing or obtaining orders for aircraft the following procedure is generally followed: A preliminary proposal consisting of a three-view drawing, typical structural isometrics, and a preliminary performance estimate is submitted to the customer. After consideration, the customer requests a manufacturer's proposal which will include complete drawings and a closer performance calculation.

Bid Data.—Upon receipt of the customer's request, bids for the airplane in specified quantities, at the guaranteed performance, are submitted. This bid data will include specifications, exceptions to existing restrictions, preliminary drawings showing the arrangement of the major installations and sales features, and various isometric and pictorial drawings to show clearly the exceptional points of the airplane. Performance calculations and weight and cost estimates will also be included.

Contract Data.—The contract data required consist of those required before delivery of the airplane and those required after delivery. In the former category belong the mock-up, or complete full-scale wooden-dummy airplane, and photographs. The mock-up is inspected and finally (after revision) is passed on by the customer's mock-up board.

The airplane detail specification may now be completed by correction according to the mock-up changes. Final drawings are next submitted for customer approval and then released for construction. The airplane finish specification is written to act as a guide for such processing in the shops. Complete weight, test, and stress reports are written; and a photographic record of the parts is maintained. Materials and process specifications are adhered to in the fabrication finishing and assembly of the airplane. Usually, all such specifications are written by the customer for general aircraft usage.

At this stage, preparation of maintenance and operation manuals must be started so that, upon completion of the first ship,

all necessary written instructions to the customer's crew can be issued. These manuals are compiled by gathering information from the engineering design groups regarding special equipment and its use and servicing. Such information, based on service-department experience with similar airplanes or equipment, and further information from vendors makes a usable manual. Requirements for the contents and style are established according to standard form by most customers. When planned for foreign service, the manuals must be issued in two or more languages.

Delivery.—Upon completion of the airplane, it is delivered and, dependent upon flight tests, accepted by the customer.

Postdelivery Data.—After the delivery of the airplane, further data must be submitted. Data, a parts list, catalogues, and photographs of tools must be sent along with all final corrected drawings and reports.

Engineering Planning. *Personnel Records.*—Another function of the contract administration, or general group, is engineering planning. Personnel records showing the time of each engineer and draftsman charged against a current work order or contract number must be kept for accounting purposes.

Drawings Schedule.—Drawings for each model airplane in design must be scheduled so that release dates may be made. These schedules are reduced weekly to show the percentage completion of the design work of each engineering group. From these a total-percentage completion curve may be extrapolated. Time estimates for each drawing are made by the group engineers and summed up to check the release date predictions. By compiling the predictions and estimates for all models being designed or going through the routine production changes, schedules for the over-all engineering work load may be established. From these schedules, the jobs may be broken down into man-hours and allotted to the proper groups and their personnel. Release progress sheets are kept as a further check on the plotted schedule, so that, as drawings are released, the percentage of released drawings as against total drawings estimated should follow the curve of estimated release dates.

Budgeting.—Costs of various items of data required by the engineering, factory, and production departments and by the customers must be computed and recorded. These include costs

of blueprints, parts list, manual, handbooks, etc. By statistical use of these costs, a budget may be set up and met.

Standards.—The general group must compile data on standards, books of Naval-Aircraft Factory standards, AN specifications, and the standards maintained by vendors and subcontractors. Over a long period of years the company itself develops standard specifications for commonly used production items such as rivets, bolts, hydraulic fittings, and drawn and extruded sections that are peculiar to the organization. These standards are developed by finding the optimum structural and practical adapted piece or part for the design at hand. Then, when future design problems of a similar nature arise, an attempt is made to use the piece or part previously developed. If it does not quite do the job, then one of similar proportions, material, etc., will be designed. After some time and when this process has been repeated, a family of similar items emerges. By correlating and segregating these families of parts, a system resulting in minimum design and production cost is set up.

Engineering Manual.—The engineering manual, or drafting-room manual, is compiled and issued by the engineering contract group. This book is a set of rules or standards to which the engineer and draftsmen must in general adhere. The manual is necessary to ensure standardization of the procedure of the engineering department, not only as to the appearance of the drawings but to assure the engineer in one group that his work will be understood by those in other groups and departments. This system is also necessary to standardize the work of the design groups in order that tolerances, dimensions, allowances, and other design considerations on parts of a similar production nature will conform with each other. By studying all the standard practices in regard to the various production methods such as machine work, sheet-metal work, and various assembly jobs, the contents of the manual specifically aimed at standardization are always self-compiling. The engineering manual is distributed to each engineering group so that reference to it may be facilitated. Copies are also sent to the company and the customer's inspection offices and to the production- and factory-department offices.

Change Group.—The change group of engineering makes all the routine production changes that may be needed as a result

of drafting or engineering errors or enforced substitutions of material or parts. Such changes also may be required because of customers' changes in specifications. This group issues engineering orders regarding such changes. The orders are duplicated on small standard-sized sheets for quick distribution to all concerned. Then, at a later date, the orders must eventually be incorporated on the original drawing and new prints issued to the shop. Other necessary changes are produced by shop requests for drawings. Such requests are usually owing to the discovery of a more efficient or better method of obtaining the desired result and receive due consideration by the engineer.

Records of Aircraft in Service.—Records of all aircraft in service must be maintained. *Trouble reports* are received from all operation centers and must be routed to the engineer or service representative for action. The correction of defects in the original article is handled by the service department. Other reports come in the form of *requests for changes;* these may be due to more up-to-date requirements by the customer. Original *proposals for new designs* are compiled from the work of the engineering group for submittal to the prospective customer. *Engineering analysis reports* must be prepared periodically to show the trends in engineering orders, shop orders, program, etc. By this means a further check is kept on the efficiency, accuracy, and speed of each engineering group. For each airplane model or type, manuals of erection, operation, and maintenance or covering the installation of new or replacement parts must be written and issued to the customer. Such *instructions* may also involve the use of motion pictures, slide films, and pictorial drawings. Often a separate "manuals group" is organized for this special work.

Miscellaneous.—The miscellaneous activities of the general group include operation of the blueprint machines and engineering files, maintenance of a complete engineering library, issuance of a weekly summary review of current journals, and the procurement, maintenance, and installation of equipment for the engineering department.

CHAPTER XIV

TEST AND RESEARCH

By K. R. Jackman

Chief Test Engineer, Consolidated Aircraft Corporation

In the previous chapters we have learned how each group of an aircraft engineering organization acts as a functional unit, contributing its share to the total engineering effort, like a wheel in a complicated but smoothly running machine.

It is not an accident that the organization and operation of the engineering test laboratory should be discussed after all the other engineering functional groups have been studied. The engineering test laboratory is a composite of all the other engineering groups, adding to the sum total of knowledge in each engineering phase of design by functional tests, development, and research. The test department also extends its influence into the shop operations, by acting as a service organization for factory units requiring controlled tests and development. It is only by the close cooperation and coordination of the test laboratory with each engineering design group, the factory production departments, the Army Air Forces, the Navy, and the plant engineering department that the most effective use can be made of the precision scientific instruments and the trained test personnel.

Inasmuch as the scope of operations of a test laboratory is so broad as to cover all fields of engineering—aeronautical, mechanical, electrical, civil (structural), industrial, refrigeration, ventilation, chemical, etc.—it is natural that much confusion should exist in the minds of readers as to a logical vantage point from which to survey so vast a panorama. To guide even the most nontechnically trained layman through the maze of this composite group, the author presents the following topical outline. Because of lack of space in which to cover so broad a subject as test engineering, a field on which complete books can be written,

only the more unusual and organizational phases of the work will be discussed. A bibliography of references, which may be valuable to one wishing to go more deeply into the various phases of testing, is included at the end of this chapter.

I. Organization
- *A*. Object of a test department
- *B*. Qualifications for specialized test personnel
- *C*. Organization of a typical engineering test laboratory
- *D*. Laboratory layout and planning
- *E*. Routine test project control and paper work

II. Test reports
- *A*. Purpose
- *B*. Organization
- *C*. Limitations
- *D*. Circulation, filing system, and reference

III. Physical testing
- *A*. General definitions
- *B*. Testing machines and practical test applications
  1. Tension-compression machines
  2. Hardness testers
  3. Extensometers and strain gauges
  4. Application of hydraulic loading units to aircraft testing
  5. Measurement of structural deflections

IV. Chemical and physical tests
- *A*. Acceptance tests of raw materials
- *B*. Control of shop-process tanks
  1. Anodic-treatment tanks
  2. Control of heat-treatment tanks
  3. Plating baths
- *C*. Other functional duties of chemists
  1. Welder tests
  2. Cable tests
  3. Calibration of shop scales
  4. Miscellaneous tests
  5. Manufacture of factory solutions, etc.
- *D*. Report routine and procedure control

V. Metallurgical control
- *A*. Purposes
- *B*. Control methods and paper work
- *C*. Photomicrography and -macrography
  1. Apparatus and specimen preparation
  2. Interpretation

VI. Spectrographic analysis
- *A*. Purpose
- *B*. Apparatus and procedure
- *C*. Interpretation and limitations

VII. High-altitude laboratory
  A. Purpose
  B. Test apparatus
  C. Test procedures
VIII. Instrumentation test group
  A. Purpose
  B. Duties
  C. Installations
IX. Miscellaneous tests
  A. Corrosion and salt-spray tests
  B. High-speed action tests
  C. Low-temperature tests
  D. Pressure-cabin problems
  E. Sound tests
  F. Vibration tests
  G. Control-system tests
  H. Special structural tests

Before beginning to describe what a qualified test engineer, chemist, or metallurgist should know and do, it is hoped that he (or "she," in this day of woman engineers) will not qualify under the following paraphrased definition:

> One who poses as an exacting expert on the strength of being able to turn out, with prolific fortitude, strings of incomprehensible formulae calculated with micrometric precision from extremely vague assumptions which are based on debatable figures acquired from inconclusive and quite incomplete experiments carried out with instruments of problematic accuracy by persons of doubtful reliability and of rather dubious mentality with the particular anticipation of disconcerting and annoying a group of hopelessly chimerical fanatics described altogether too frequently as airplane designers.

Rather let us remember Aristotle's statement that it is the mark of an instructed mind to rest satisfied with that degree of precision which the nature of the subject admits and not to seek exactness where only an approximation of the truth is possible.

Remember that the engineer should govern the test, not the test the engineer. Davis (Ref. 2) states that "Testing should not be used as a substitute for thought, although it may be found that an appropriate experiment may aid in an analysis. The magic of tests lies not in turning them on and hoping for the best, but results from careful, intelligent planning and the slow, painful process of overcoming difficulties."

ORGANIZATION

Object of a Test Department.—The testing of structures, materials, or other products may be performed with several objects in view, as follows:

1. To prove that a new or redesigned structure or part meets specified performance of strength and strength requirements.
2. To control the properties of routine raw products and materials.
3. To develop new allowable structural-design features, new materials, and better testing technique.
4. To check the functional operation of aircraft components under service conditions.

Qualifications for Specialized Test Personnel.—Before the floor plan or the test equipment of an engineering laboratory can effectively aid in the "battle of production," the test personnel should be selected with care.

It has too often been found that the selection, handling, training, and control of the test personnel can make or break the morale and hence the efficiency of the group. The importance of careful selection of test-engineering applicants by personal interviews cannot be overstressed. A test engineer, chosen by mail application, without forewarning of what his work will entail and his responsibilities to his group members, cannot be blamed for dissatisfaction when he finds the type of work not suited to his temperament or education. On the other hand, a test applicant, having seen the laboratory, his co-workers, and the equipment and having been carefully instructed as to his early duties, should not, after accepting the position outlined, consider a transfer or change of position in less than 8 to 12 months' time. The elementary training of a general test engineer requires 3 to 5 months, with specialty test work requiring sometimes years of experience. Therefore, it is unfair to the young test engineer and to the company to make changes before 8 months of elementary test practice have been covered.

The qualifications of a graduate engineer working in the drafting room may be rated quite differently from those of an engineer in the test laboratory. Sound educational background is essential in both places, but the test engineer must, above all, be practical, be able to take responsibility, work independently of

his comrades, analyze test results, and write a concise, clear report on his findings.

The six work qualifications and their relative importance that are sometimes applied to engineers are quality, 25 per cent; quantity, 20 per cent; knowledge of work, 20 per cent; adaptability, 15 per cent; dependability, 10 per cent; and attitude 10 per cent, but these traits are not sufficient for a test engineer's "self-analysis" system.

There has appeared increasing need for some form of standardization and personnel survey in the engineering test laboratory to aid in the advancement and efficiency analysis of test engineers, metallurgists, and chemists. The "personnel rating system" described below has been given a trial and has proved a satisfactory means of allowing each person to correct his failings, compare himself with his co-workers in testing ability, and improve his value in his chosen profession.

The background and characteristics of each member of a test laboratory may be weighted on the basis of 100 points as follows:

I. Education (maximum 10 points)
  A. Engineering college courses at 3 points per year
  B. Bachelor of Science courses at 2 points per year
  C. Vocational school courses (full time) at 1 point per year
II. Occupation and seniority (maximum 20 points)
  A. Work prior to entering test department (5 points maximum)
    1. Teaching engineering subjects (college grade) at 1 point per year
    2. Shop experience at 1 point per year
    3. Extension courses passed at ½ point per course
  B. Service in the testing field (10 points maximum) at 2 points per year
  C. Knowledge of work (5 points maximum)
III. Planning of tests and preparation of reports (maximum 25 points)
  A. Organization of tests (5 points maximum)
  B. Grammar, handwriting, printing (5 points maximum) or neatness in laboratory reports and apparatus (chemists only)
  C. Accuracy (5 points maximum)
  D. Speed (10 points maximum)
IV. Business ability (maximum 45 points)
  A. Practicality (15 points maximum)
  B. Responsibility and judgment (15 points maximum)
  C. Initiative (5 points maximum)
  D. Adaptability (5 points maximum)
  E. Attitude and application (5 points maximum)

Total.............. 100 points

It is quite possible that, on self-analysis by the above system, an individual may have the tendency to overrate himself. Let us analyze the case of a test engineer, average in ability, an engineering college graduate, but a little slow, and poor in report writing.

Example.

1. Education—4 years' engineering college	10 points
2. Occupation and priority	
a. Taught mechanics for 2 years	2 points
Was machinist for 1 year	1 point
b. Served in test department for 2 years	4 points
c. Average ability	3 points
Total	10 points
3. Tests and reports	
a. Organization fair	3 points
b. Written reports poor	1 point
c. Average accuracy	3 points
d. Somewhat slow	2 points
Total	9 points
4. Business ability	
a. Average in 5 traits	23 points
Complete total	52 points

Self-analysis by the above or any fair standard should aid the individual to improve his testing ability, so that progress may be made, in assuming added responsibilities and consequently in bettering himself financially and in producing better tests and reports for the organization.

Organization of a Typical Engineering Test Laboratory.—An engineering test laboratory typical of many in the aviation field contains all the personnel to conduct contract, raw-material control, development, and research tests. Figure 1 shows an organization chart for such a laboratory.

It should be noticed that the functions performed by a single test laboratory are in some aircraft organizations delegated to engineering and shop test organizations. After considerable experience with the setup of Fig. 1, however, it is believed that there exists less duplication of tests and equipment than in a system of divided responsibility.

Within each subdivision of the engineering test laboratory there is organized a self-sufficient unit, headed by a competent and experienced engineer, chemist, or metallurgist-in-charge.

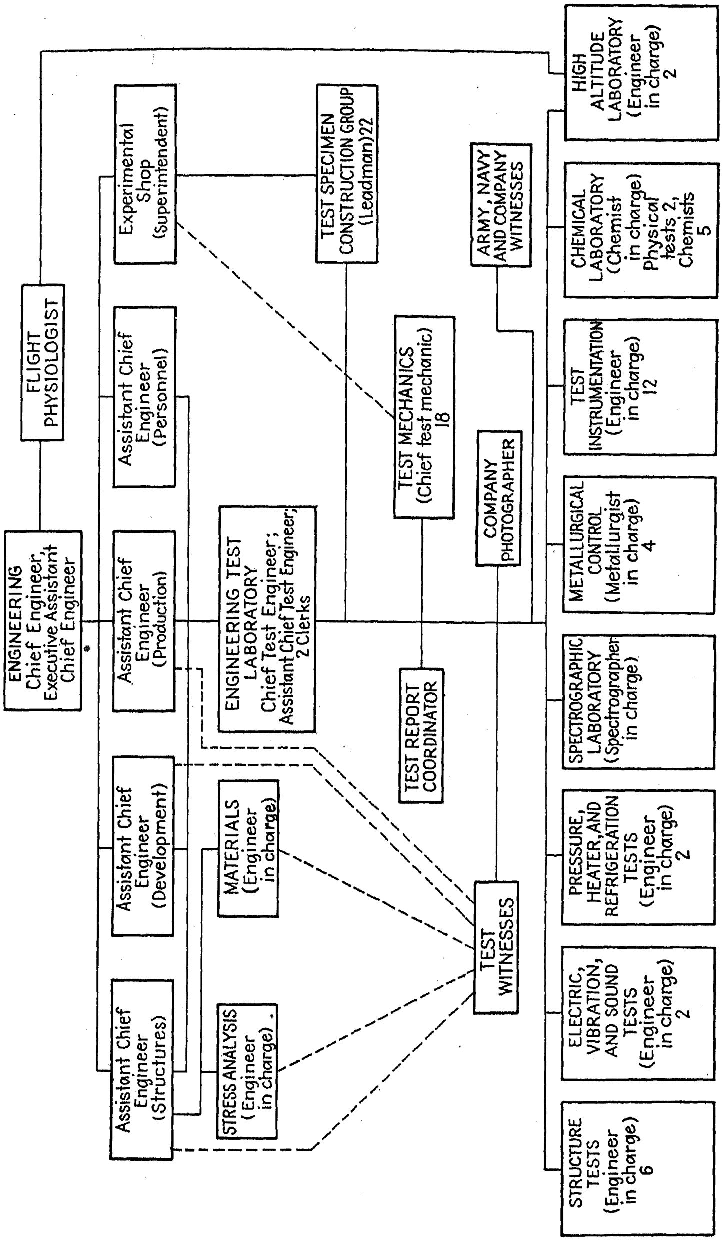


FIG. 1.—Organization of a typical test laboratory.

An effort is made in each test unit to have the leadmen understudied by competent assistants, who can, at a moment's notice, fill the leaders' places, in case of sickness, accident, or absence.

Laboratory Layout.—The requirements for a compact test laboratory may be summarized as follows:

1. Sufficient test area and accommodations
   Ample area, serviced by a hoist system, for test jigs—lockable individual laboratories to protect intricate test setups and expensive equipment
2. Efficient placement of test laboratories and workrooms
   Economy of test personnel movement and control—ease of installation of building contractors' items, such as plumbing, ventilation, and other services—location within factory for shop and engineering contacts
3. Isolation of laboratories with special requirements
   Chemical-laboratory ventilation to overcome obnoxious fumes
   Vibration-room shock insulation to remove shop setup problems in adjacent factory areas
   Sound insulation of various laboratories that may disturb adjacent departments
   Ventilation of salt-spray room and photomicroscopic specimen—cutoff—polishing room
4. Provision for adequate doors, slide panels, etc., to accommodate the the movement of large specimens
5. Provision for future expansion of personnel offices and specimen test areas

The manner in which a test laboratory attempts to meet the foregoing requirements may be seen in Figs. 2 and 25.

1. The total laboratory area has been subdivided as follows:

	Square Feet
Office area	2,830
High-bay area (approximately 18 ft. 0 in. headroom)	4,950
Special laboratory areas (approximately 9 ft. 0 in. ceiling height)	5,990
Approach areas (for personnel and personnel movement)	4,445
Yard test area	3,150
Protected storage area	1,550
Total laboratory area	22,915

An electrified 2-ton monorail hoist system services the high-bay areas of the main laboratory and also a 75-ft. length of the high-altitude laboratory.

As may be seen in Figs. 3 and 4, ample cabinet space has been provided to safeguard test apparatus not in use.

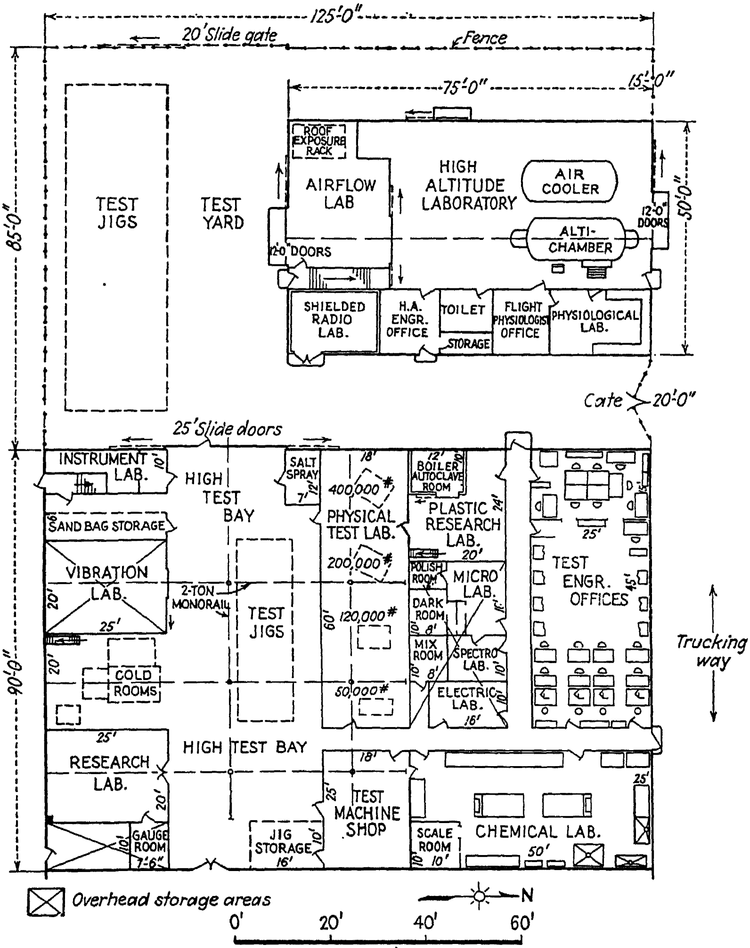


FIG. 2.—Floor plan of a typical test laboratory.

2. To maintain an efficiency of placement of special laboratories, it may be seen in Fig. 2 that the following details are provided for:

The mixing room, where dusty shop products are prepared, is maintained separate from but near the chemical laboratory to allow common personnel operation.

One darkroom services both the photomicrographic and spectrographic laboratories.

Areas over laboratories with 9 ft. 0 in. ceilings are used as storage areas to conserve space.

The laboratory is near the engineering department and the experimental shop where specimens are prepared and not far from the center of the main factory activities.

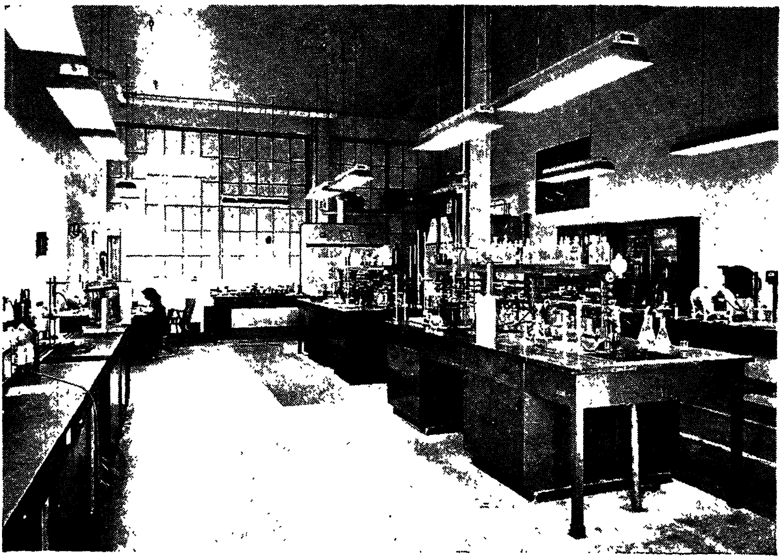


FIG. 3.—View of aircraft chemical laboratory.

3. The ventilation problem has been handled by the following: suction-ventilation provisions in the chemical laboratory, salt-spray room, mixing room, and instrument room to remove dust and odors; pressure-ventilation provisions in the photomicrographic laboratory, spectrographic laboratory, and darkroom (the substitution of pressure ventilation in these areas for suction makes possible the clean handling of photographic film); insulation of the vibration-sound room with Celotex-covered Thermax walls and a vibration-isolated concrete-slab floor.

Routine Test Project Control and Paper Work.—It is obvious that in a test laboratory where more than 100 test projects are carried simultaneously for as many as six different aircraft

designs some red tape and paper work are required to provide control, follow-up, and scheduling of projects.

It requires the full-time services of two people to schedule and follow up test projects currently in the system. Some development and research test projects may extend over several months, whereas other urgent structural tests may have to be given maximum priority and completed in a few hours' time. A

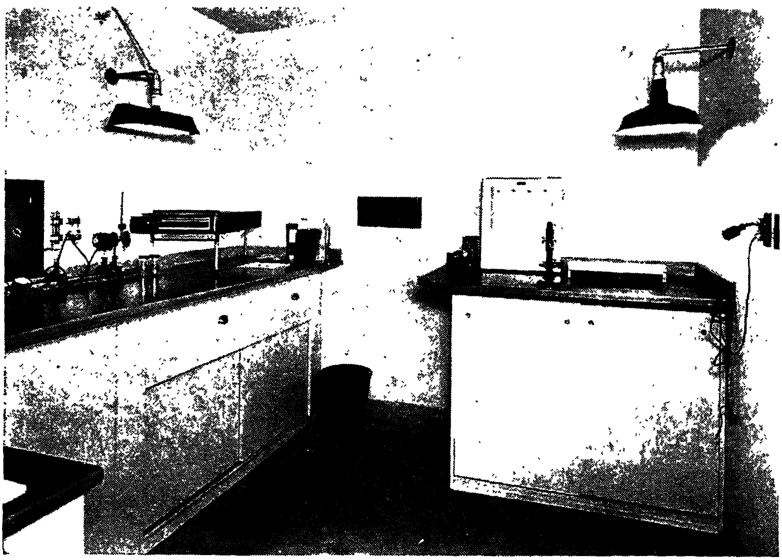


FIG. 4.—Simple qualitative spectrographic laboratory.

typical system for controlling test projects will be discussed in some detail for the benefit of those readers who may have similar control problems.

Tests may be requested by any person, provided that the "test request" is approved by the interested shop foreman or engineering project engineer or other delegated authority. The request is made on the form (Fig. 5), to eliminate the confusion of verbal requests and to provide a record of projects.

The test request is then submitted to one of the following interested executives for approval:

Assistant chief engineer (structures).
Assistant chief engineer (development).
Assistant chief engineer (production).

After the executive approval has been affixed at the bottom of the page, the test request is sent to the planning and scheduling group, engineering department, for insertion into the test sched-

TEST REQUEST

Engineering Test Laboratories

NOTE: File *all requests* in *test journal* upon completion of test.

Test Order No. 1542
Test Engineer J. Jones
Report No. SG-432

Name of Test: Cold Test of "ABC" Synthetic Rubbers

Test requested by R. Smith (Materials)

Approved by A. Booth (Group Engineer) and D. Clark (Project Engineer)

Date of Request 6/10/42 Airplane Model No. 45 W.O. 632

Test Specimen Drawing No. T43 Reference Tests SG-374

Object of Test (summarize): Determine the characteristics of 3 submitted "ABC" Chemical Co. products:
a. Tensile and 90-deg. bend test at −70°F.
b. Tensile test at +70°F. (control)
c. Durometer readings at +70 and −70°F.

Description of Sketch of Desired Test Setup:
Test following samples of "ABC" Chemical Co. submitted on May 14, 1942 (Ref. "ABC" letter to C.A.C. of May 5, 1942):
Specimen X—No. 45B—50 Shore A.
Specimen Y—No. 47A—60 Shore A.
Specimen Z—No. 51B—60 Shore A.
Use standard rubber tensile coupons (Type R-4) in 2,000-lb. hydraulic T. Olsen testing machine at 6 in. per min. extension speed. Check elongation (2 in. gauge length) vs. load. Maintain temperature of −70°F. coupons in transfer from cold room to Olsen machine with "CO_2" blocks.
Use C.A.C. 90-deg. bend jig (No. C-5) and durometer (Type A).

Witness Required:
[X] Air Corps [X] Navy [ ] C.A.C. Inspection Others P. Soundel

Type of Report Desired:
[X] Test Data Memorandum—for Limited Distribution
[ ] Complete Report—for Air Corps, Navy, or General Distribution

Disposition: Test Specimen—Send to R. Smith Test Jig—Return to Test Crib

Authorized by J. Doe
Assistant Chief Engineer (Development)

FIG. 5.—"Test-request" form.

ule. The assistant chief test engineer and/or the test report coordinator are then contacted to determine a probable completion date, based upon the priority affixed to the new test and those preceding it. The test request, preferably accompanied by the test specimens, if possible, is then delivered to the test

laboratory and is put "into work" according to its position of relative importance.

The priority designated on various test projects is subject to constant change and readjustment, as changing engineering or shop designs may demand. Test engineers have been known to start and stop several jobs in one day, as the urgency of various tests fluctuated.

Each test project, covered by one or more test requests of a similar nature, is then assigned a test number, a work order number (for cost accounting), and a responsible test engineer, as shown in the form above. The test engineer, chemist, or metallurgist assigned to the test is responsible for the test-specimen release and follow-up (if this has not been done by the department originating the test), test-jig release and follow-up, the test operations, provision for service, factory, and/or engineering witnesses, provisions for photographs, and the final test report. All test personnel must therefore be, as previously mentioned, practical, responsible, and capable of writing good test reports.

In Fig. 6 there is shown a typical entry in the control sheet maintained by each test engineer. The purposes of this sheet are threefold. (1) It allows each test engineer systematically and uniformly to keep his own records. (2) It provides an approximate scheduled completion date on each test. (3) It provides a source of information from which the test project schedules (Fig. 7) are prepared.

The procedure followed by the test engineer in maintaining the control sheet shown in Fig. 6 is as follows:

On receipt of a test request properly countersigned, he enters the test number from the master test journal, work order, title, and date received in columns 1 to 4, respectively.

If shopwork is required before starting to make the test, he schedules in column 5 (To shop) the date he expects to send the test order to the shop.

When shopwork is completed, he enters the date of completion in column 6 (From shop), schedules in column 7 the date test will be started, and, if possible, schedules also the date of completion of test (column 8).

When test is completed, he schedules in column 9 the date of finishing the report and in column 10 the report number. Once

Engineering Test Laboratory

Test Control Sheet
Test Engineer J. Jones

Consolidated Aircraft Corporation
Period 6/1/42 to 7/1/42

Test No.	Work order No.	Title	Request received	To shop	From shop	Started test	Completed test	Finish report	Report	Per cent* complete
1	2	3	4	5	6	7	8	9	10	11
1542	632	Cold tests "ABC" synthetic rubber	6/11/42	6/11	6/12	6/13	6/16	6/18	SG-374	90

* Status Legend: 30 per cent to shop, 60 per cent completed by shop, 80 per cent test completed, 90 per cent report written, 100 per cent report accepted.

FIG. 6.—Test engineer's control sheet.

Engineering Test Laboratory

Consolidated Aircraft Corporation

Schedule of Test Projects

Page 3

Model No. 45		Work Order No. 632	Test requested		Schedule dates				Progress per cent complete				Test engineer
Test No.	Priority	Subject	Group	Date	Start	To shop	Start test	Report accepted	6/5	6/12	6/19	6/26	
1542	A	Cold tests "ABC"	R. Smith (materials)	6/10/42	6/11	6/11	6/13	6/20	. . .	80	90	100	* J. Jones

Status Legend: 30 per cent to shop, 60 per cent completed by shop, 80 per cent test completed, 90 per cent report written, 100 per cent report accepted.

Model No. 45.

FIG. 7.—Schedule of test projects.

a week the test engineers' control sheets are collected by the report coordinator and summarized in the schedule of test projects shown in Fig. 7.

To acquaint the engineering personnel with the progress of test projects and to maintain control in the test laboratory, each week there is prepared and circulated a test progress report (Fig. 8). These reports, sometimes containing as many as 130 projects carried by 10 to 12 test engineers, are summarized as in the figure and circulated to the engineering executives, project engineers, and other interested persons for their information and possible priority changes.

Status of Tests for Week Ending 6/13/42					
Test Model No.	Test projects at start of week	Test projects added during week	Total test projects	Test projects completed during week	Current test projects
45..........	33	6	39	4	35
47..........	21	0	21	5	16
Total.....	54	6	60	9	51
Summaries Weeks Ending					
May 30.....	53	5	58	4	54
June 6......	50	7	57	4	53

FIG. 8.—Weekly test progress report.

A "priority" blackboard is maintained in a prominent place in the test engineering office to rush special test projects of immediate importance. The items on this board are changed weekly. It is the responsibility of the project offices to see that their most urgent tests are maintained on the current priority lists.

A test report control blackboard is also kept up to date in the test engineering office to show at a glance the load being carried by various test personnel. Thus by looking at Fig. 9, it will be noted that V. Smole is carrying 11 test projects this week in various stages of testing but has only 3 projects awaiting reports.

His work for the past 3 weeks has been piling up, whereas that of V. White has reduced. V. White is now about ready to undertake several new test projects.

Test Report Control Week Ending 6/13/42										
Test engineer	Badge No.	Test status		Totals Status of Weeks						
		Tests below 80 per cent	Tests above 80 per cent	6/13	6/6	5/30				
J. Jones	1435	7	4	11	10	8				
V. Smole	1514	11	3	14	12	11				
V. White	1572	4	4	8	11	16				

FIG. 9.—Test report control.

TEST REPORTS

Purpose.—A somewhat monotonous but immensely important part of a test engineer's work is the compilation and organization of test data and the preparation of test reports. The purpose for such formal reports is fourfold.

1. To convey the results of tests to the design engineers and draftsmen.
2. To condense the results for executive consumption.
3. To fulfill contract obligations with the purchaser of the airplanes on which the tests are performed.
4. To provide a permanent record of the tests and results for future reference.

Organization of Reports.—Test reports are usually organized under the headings of Object, Description of Test Specimen, Test Procedure, Results, Discussion, and Conclusions. If the report is lengthy, it is sometimes convenient to have a Summary of Results and Introduction on the first page. Tests that involve elaborate loading systems or complicated load distributions sometimes necessitate a section Loading Schedule in the final report.

The methods of presentation of test reports vary among aircraft manufacturers. The following examples represent the

Rec. Rep. 90367
P. O. 41549
Material: Chrome-Molybdenum Bars (X4130) Material Data Report Date 6/15/42

Chemical Analysis

Description	Analysis No.	Carbon	Manganese	Phosphate	Sulphur	Nickel	Chromium	Vanadium	Molybdenum
$\frac{3}{4}$-in. round bars (heat No. 21C030)	M-5443	0.30	0.55	.....	.....	.....	0.94	......	0.20
Specification 57-107-19	Requirements	0.25 to 0.35	0.40 to 0.60	0.040	0.050	.....	0.80 to 1.10	......	0.15 to 0.25

Physical Properties

Description	Dimensions			Yield point		Ultimate		Elongation		Reduction of area		
	Diameter	Width	Area	Pounds	Pounds 1 in.	Pounds	Pounds 1 in.	″	Per cent (2″)	Size	Area	Per cent
M-5443	0.504	......	0.200	25,600	128,000	27,900	139,500	2.37	$18\frac{1}{2}$			
Specification 57-107-19	Requirements	......	.....	......	....	......	125,000	....	20			

Remarks: Material is within specified tolerances.

C. Jones
Testing Laboratory

FIG. 10.—Chemical-physical test-report form.

procedure used at one company. Three types of written reports exist, as follows: (1) a short chemical and physical test report form (Fig. 10); (2) a test data memorandum (T.D.M.) (Fig. 11); and (3) a complete formal report.

The chemical and physical test reports originate in the chemical and physical test laboratories to cover each material test. The

Engineering Test Laboratories
Test Data Memorandum

T.D.M. No. 1542

Test: Cold, Hardness, and Bend Tests of "ABC" Synthetic Rubbers. [Be as explanatory as possible but short.] Model No. 45

Object: [State only the object of the test, *not necessarily as stated on the test request.*]

Test Apparatus and Procedure: [Usually the easiest method is to combine these two subjects. Care must be exercised to be sure that all apparatus used is mentioned and its use explained, but detailed description need be made only of the specimen, the jig, and the manner of attaching these two. The procedure used should be so stated that the test could be duplicated in the future, if necessary, by an inexperienced junior test engineer.]

Results: [*Only* results are to be stated under this heading. *No* discussion of the results is permissible.]

Discussion: [Discuss only the results obtained, and do not theorize or make elaborate statements for the results obtained from a few tests. No discus ion of production possibilities, unless requested.]

Conclusion: [The conclusion must prove or disprove the object. No statement may be made in the conclusion that has not already been mentioned under Results or Discussion.]

Witness: [Witnesses must be on hand for all tests except those of research nature.]	By	Test Engineer
		Report Coordinator
	Checked	Assistant Chief Test Engineer
Date: [Date all reports.]	Approved	Chief Test Engineer

FIG. 11.—Typical T.D.M.

report form, shown in Fig. 11, allows the transmittal of test results only, with no provisions for detailed discussion.

The test data memorandum (more usually referred to as a "T.D.M.") is used to get vital test results rapidly to interested persons in the engineering department and factory. Such reports are usually not circulated outside the company, the

longer, more complete report being used for that purpose. A copy of the T.D.M. form, with instructions for its completion, is shown in Fig. 11.

All the test data of a T.D.M. report should be contained on one page or on attached charts, tables, or graphs. With such short reports, typed upon vellum for blueprint reproduction, copies may be placed in the hands of interested designers, draftsmen, or shopmen in a minimum of time.

The more formal report, covering from several to over fifty pages, is prepared on important development or research test projects not capable of being telescoped into a T.D.M. and whose results should be more widely distributed. These reports are assigned one of two types of identifying numbers, either an SG-374 numerical designation to indicate reports of general information on more than one model of airplane ("SG" signifies "Structures Group"), or a contractual number such as ZS-45-053 indicating that the test report is applicable only to airplane model No. 45, is a structures ("S") report ("Z"), and is the fifty-third such report on that model.

Limitations.—The chief shortcoming of a junior test engineer is nearly always evidenced in his inability to write a concise, grammatical, and readable test report. Part of this difficulty may be due to the test engineer's inexperience, and some undoubtedly to a desire to terminate the test project quickly, but most of the report-writing troubles originate in the inability of the average individual performing a relatively simple experiment to state clearly his successive steps toward reaching a conclusion. Test experience and the rewriting of faulty reports appear to be the best teachers for the inexperienced engineer. A few of the many requirements are as follows:

1. Describe the test specimen, setup, and procedure so that a duplicate test may be made years hence by an inexperienced test engineer and the test data may be truly comparable.

2. Use good grammar and complete sentences. A new test engineer will do well to review some of his schoolbooks on English and report writing.

3. Submit all test data used in formulating the conclusions, so that the reader may recheck the findings should he so desire.

4. Avoid long, difficult sentences, unusual words, and uncommon abbreviations. Be concise without sacrificing clarity.

5. Print and write legibly. Prepare neat and clear graphs. Do not use uncommon graph divisions in plotting test data.

6. Prepare photographs with the test specimen shown as large as possible and with the unimportant background masked or blocked out.

7. Be explicit in the titles of pictures, graphs, and charts and above all in report titles. Care exercised in the selection of report titles will pay dividends many times over in the ease of finding reference reports.

Circulation, Filing System, and Reference.—Tests and test reports are of little value if they do not reach the individuals interested in the results or cannot be found in the filing system. The chemical and physical report, the T.D.M., and the SG report are circulated first to the person originating the test and to others who may be interested in the results. Initials of the engineers who have seen the report give evidence of proper distribution.

An incomplete or poorly referenced index to a test-report file can very seriously hamper an otherwise efficient test department. Several systems have been tried by the author over a period of years, but it was not until recently that an effective system of quick reference was applied to the test-report file. With several thousand test reports in four or five filing cabinets, it is a formidable job to pick the one report desired. The main difficulty appears to be one in title and subject. Four engineers looking for recent test reports on Shear Tests of 17ST Rivets at Low Temperatures may look under the following four different subjects: shear, rivets, 17ST aluminum alloy, and low-temperature tests. The report librarian's job is one, therefore, of much cross-referencing and anticipating the many subjects that an engineer might choose.

A dual card index file, similar to a library system, has proved very useful in the location of test reports. A set of cards is typed, one for each report as shown in Fig. 12, and filed in numerical order. A second identical set of cards is prepared, with each report card cross-referenced under as many subjects as found desirable. The latter cards are grouped according to subject matter. Thus an engineer, seeking a certain test report on rivets, may, by thumbing through possibly 30 "rivet" cards, pick the report desired and identify it by the card references to

the date of the test report, the test engineer, or the object of the test.

SG Pressed Countersunk Rivets vs. Machine Countersunk
613 Rivets in Plate-Stringer Combinations

Subject References
1. Rivets
2. Plate-stringers

To compare the allowable compressive stress of plate-stringer combinations composed of various sizes of rolled, 24ST Alclad stringers and 0.072-in. 24ST plate, riveted together with various sizes of machine countersunk rivets, with that of similar combinations riveted together with pressed countersunk rivets.

Aug. 14, 1939 R. S. Reade

FIG. 12.—Typical test-report index card.

PHYSICAL TESTING

No attempt will be made in this chapter to cover test information that has been very well presented in the books listed as references at the end of this chapter. These books should be available to the reader at the local public library and should eventually become a part of every test engineer's personal reference library, since each covers phases of test engineering and affiliated subjects not covered by the other references.

General Definitions.—Before discussing the various detailed phases of the work of a test engineer, it may be desirable to define (see Chap. I of Ref. 3) certain of the common engineering terms used in the remainder of the chapter.

Stress. Intensity of the force acting on a unit area.

$$f = \frac{P}{A} \quad \text{or} \quad S = \frac{P}{A}$$

Strain. The elongation, per unit length, of a member or portion of a member in a stressed condition.

$$e = \frac{\delta}{L}$$

Stress-strain relation. Usually plotted as a graph, forms the basis of most strength specifications.

Modulus of elasticity (*Young's modulus*) (E). The slope of the straight portion of the stress-strain diagram; equals the stress (f) divided by the strain (e), or $E = f/e$.

Tensile proportional elastic limit (P.E.L.$_T$ or F_{tp}). That stress at which the stress-strain curve departs from a straight line.

Tensile yield point (Y.P.$_T$ or F_{ty}). That stress at which the stress-strain curve indicates a permanent unit deformation of 0.002 in. per in. or 0.2 per cent.

Ultimate stress (tension-ultimate or F_{tu}). The stress at the maximum load reached in the test.

Modulus of rigidity (shear modulus) (G). The ratio of the shearing stress-to-strain at low loads, or simply the initial slope of the stress-strain diagram for shear.

Poisson's ratio (μ or σ). The ratio of the lateral strain to the axial strain (0.25 to 0.33 for steel and aluminum alloys).

In homogeneous materials, $G = E/2(1 + \mu)$.

Several common test terms used in connection with structural tests for the U.S. Air Forces and Navy may be defined as follows:

Design limit load. The known or assumed applied load that is not expected to be exceeded in service operation for any predetermined design condition.

Design yield load. A load equal to the design applied load multiplied by the yield factor of safety prescribed in the detail specification.

Design ultimate load. A load equal to the design applied load multiplied by the ultimate factor of safety prescribed in the detail specification.

Material correction factor. A factor representing the ratio of the strength of a similar article having the minimum acceptable material (strength) properties and dimensions to the strength of the test article.

Design limit (or proof) test. A test in which a load equal to the design limit load divided by the required material correction factor is properly applied to the structure.

Design yield load test. A test in which a load equal to the design yield load, divided by the required material correction factor, is properly applied to the structure.

Design ultimate load test. A test in which a load equal to the design ultimate load, divided by the material correction factor, is properly applied to the structure.

Destruction test. A test in which the load is increased until failure occurs.

Critical design load (or condition). The design load (or condition) for which the margin of safety is the least.

Testing Machines and Practical Test Applications.—Clark (Ref. 1) and Davis (Ref. 2) have thoroughly described the more common and some uncommon testing machines used by an aircraft test engineer. Each aircraft test laboratory will, at first, be satisfied with standard test machines and procedures;

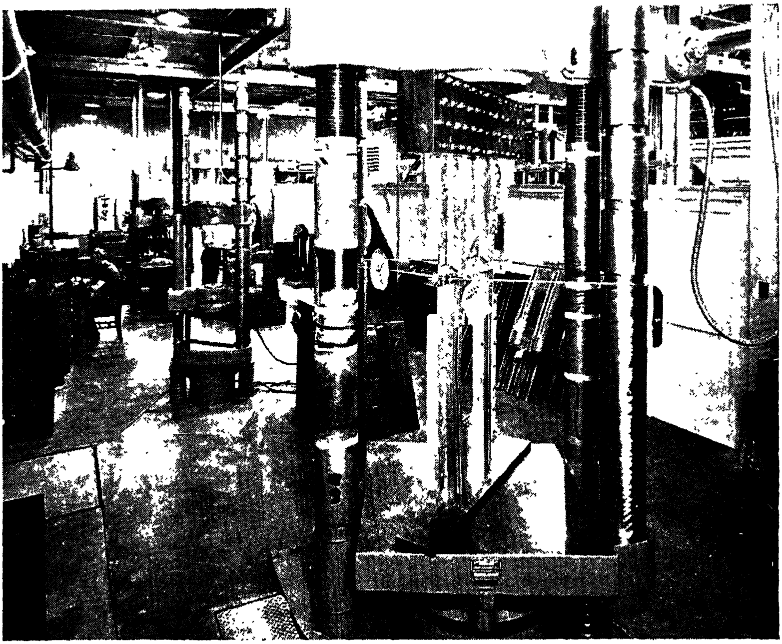


FIG. 13.—Universal testing machines.

but as testing technique and experience increase, there will be developed special adaptations of standard test apparatus or new test units to meet local conditions. The latter machines are of primary interest to practical test engineers. A few interesting cases will be discussed in some detail.

Tension-compression Machines.—Figure 13 shows a portion of a modern aircraft laboratory in which there exist five universal tension-compression testing machines. The machine in the foreground is a 400,000-lb. capacity hydraulic Southwark-Tate-Emery, with 12 ft. 0 in. compression and tension specimen clearance. The next in line is a 200,000-lb. hydraulic Southwark-

Emery, with 80 in. compression and tension specimen clearance. A portion of a 120-000-lb. hydraulic Southwark-Tate-Emery testing machine with 48-in. platen clearance may also be seen. The last machine shown in the figure is an old screw-and-lever type 50,000-lb. Riehle testing machine that has seen over 12 years of hard service. Elsewhere in this laboratory there exists a 2,000- to 5,000-lb. hydraulic T. Olsen machine for covering the lower tensile ranges on more delicate specimens. Thus between the five testing machines a range of tests covering loads of a few pounds to 200 tons is available. The several machines in the higher load ranges have been found necessary to care for the simultaneous loading of several test specimens.

The uses of the 400,000- and 120,000-lb. machines in this laboratory have been extended, under conditions where exact control and automatic plotting of the load-deformation relationship in tension are desired, by the attachment of a high-magnification, stress-strain recorder of the Southwark-Templin type.

In Fig. 13 will be seen a convenient method of restraining a plate-stringer splice specimen against lateral motion in the plane of the splice. This simple support allows column action in the bays above and below the splice, with the conservative assumption of no torsional rigidity in the splice bulkhead.

Several other important practical considerations relative to the compression tests of plate-stringer specimens, such as those shown in Fig. 13, might be of interest, since they are not covered in the works listed as references at the end of this chapter. Plate-stringer test data must be obtained with end fixity comparable with that existing in the airplane structure. It has been found that stress analysis and structural designs based on single- or double-bay specimens, in which the ends are milled or ground flat and parallel, closely approximate the design stresses developed in full-scale destruction tests. Several precautions should be observed in using hydraulic testing machines similar to the 400,000-lb. Southwark-Tate-Emery shown in the foreground of Fig. 13.

1. The bearing between the hardened faceplates and the specimen should be so close that, under 500 lb. of load, light is not visible between the two surfaces.

2. The centroid of mass should be centered on the "rings" of the upper and lower platens. If sheet buckling during test

will appreciably move this mass centroid, it is well to repeat the loading until the effective mass is concentric near the ultimate load on the specimen.

3. Many laboratories test wide plate-stringer specimens in a plane normal to the front of the apparatus. This position is satisfactory if the machine platens remain parallel throughout the loading. It has been the author's experience, however, that the type of hydraulic testing machines shown in Fig. 13 is subject to considerable sway and that specimens placed in the plane of the platen-raising screws are least affected by misalignment of specimen or ineffectiveness of sheet. The slight rotation of the plate-stringer splice specimen shown in Fig. 13 from this plane was necessitated by the method of bulkhead restraint.

4. Maldistribution of load in a wide plate-stringer specimen sometimes occurs because of the bending action of the bearing block overhanging the upper platen. Rigidity of this block by addition of mass and depth is relatively inexpensive to achieve and will repay the operator with more consistent test results.

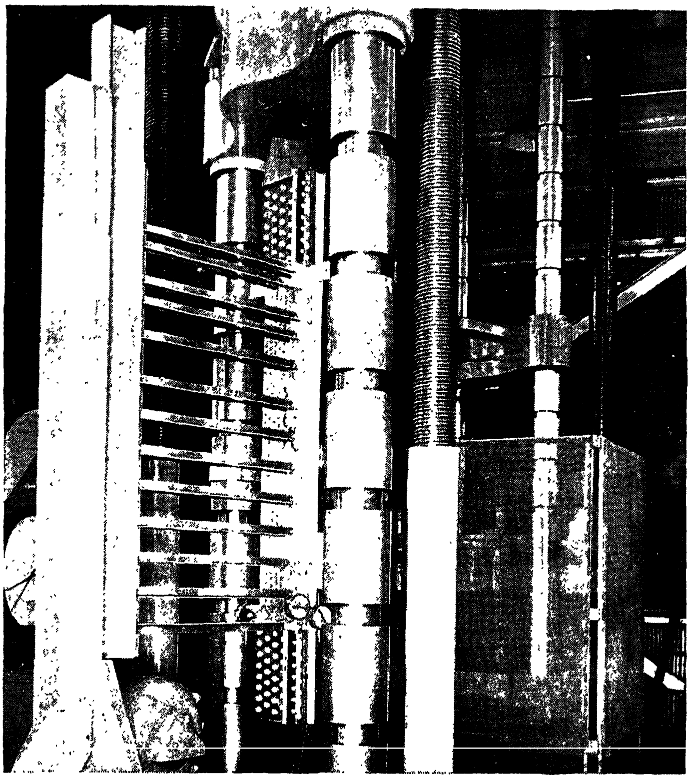
Figure 14 shows another example of the way in which test engineers have applied the adage "The difficult we can do immediately, the impossible takes a little longer." In this instance a tension splice of a wing section was being tested and the lateral support afforded by the spar web structure was desired, without its shear-carrying properties. This was done by the pin-ended "ladder supports" which were incapable of taking shear. Another innovation of the ingenious test engineer in charge of this test project was the use of indicator dials at the lower tension fitting actuated by wires attached to the upper tension fitting, it being thus possible to detect any deformation or elongation in the full length of the tension specimen.

A clever and practical test engineer thus has many opportunities of applying original ideas to test problems with great benefit to the field of test engineering and to his colleagues.

Hardness Testers.—Clark (Ref. 1) and Davis (Ref. 2) thoroughly cover the usual types of hardness testers found in the aircraft field. The Rockwell tester is most common in the checking of aluminum alloys and alloy steels used in airplanes.

The fallacy most commonly found among aircraft inspectors is that the Rockwell reading is a final criterion for rejection. The hardness reading is rather an inspection tool for the detection

of improperly heat-treated or soft material. The author some years ago found Rockwell operators attempting to identify and separate 17ST and 24ST aluminum-alloy parts. The tensile strength and hardness of these materials may overlap at their extreme tolerances, and therefore the Rockwell numbers of



14.—Lateral support of tension specimen in 200,000 lb. Universal testing machine.

B-64 and B-72 are relative only and should be viewed in their true perspective.

Another common error found among inexperienced test engineers and inspectors is the improper preparation of samples on which hardness readings are desired. The two surfaces of the specimen should be free of scale, below the effects of surface oxidation or casehardening, and parallel. Several readings should be taken on the specimen and the results averaged. The

first reading obtained after replacing the "Brale," or "ball point," should be discounted, since the point invariably seats itself on the first application of load.

Extensometers and Strain Gauges.—No single branch of testing appears to offer so much valuable practical test data as that of the application of strain gauges to structural tests.

Every test laboratory probably has one or more types of simple strain gauges in constant use on tensile coupon tests. Most of these gauges in laboratories today are of the dual-pointed indicator dial type, reading either in 0.001- or 0.0001-in. increments.

There are nearly as many varieties and sizes of extensometers for material, structural, and research testing as there are ingenious test engineers. The shape and attachment limitations usually dictate the type of strain gauge used.

The Huggenberger "Tensometer" is a laboratory tool familiar to structural test engineers. This instrument meets the demand for a light, compact strain gauge, capable of being attached to one side of a flat or curved surface. The 1,000:1 amplification type of this gauge weighs only $2\frac{1}{4}$ oz. However, this instrument, in common with all extensometers that depend upon knife-edges or points for attachment to the test specimen, is very sensitive to vibrations and easily dislodged. Figure 15 shows the installation of 1,000:1 Huggenberger gauges on tensile test coupons for calibration purposes.

Vose (Ref. 17) makes a complete study of Huggenberger gauges and points out that the mounting pressure applied to the instrument may vary the calibration constant by several per cent. This variable, together with the questionable factors of instrument mounting to resist vibration creep, presence of bending in the specimen, and the effect of parallax in the readings, has spurred the development of a remote-indicating extensometer that is vibration insensitive and able to record true strains in the presence of specimen bending. Such gauges now appear in various electrical forms, the most common of which are the wire resistance gauges.

The Baldwin-Southwark Company has on the market several resistance wire gauges. Their original SR-4 unit, known as the "bonded Metaelectric strain gauge," was approximately $1\frac{3}{8}$ by $\frac{3}{4}$ by $\frac{1}{4}$ in. in size, weighed approximately 0.050 oz., and had a

resistance of 110 ohms. This model had a brass crossbar for mounting which had to be disconnected during test. The more recent type A-1 SR-4 gauge has been reduced to a size of $1\frac{1}{2}$ by $\frac{1}{2}$ by $\frac{1}{8}$ in., weighs 0.016 oz., and has a resistance of 120 ohms.

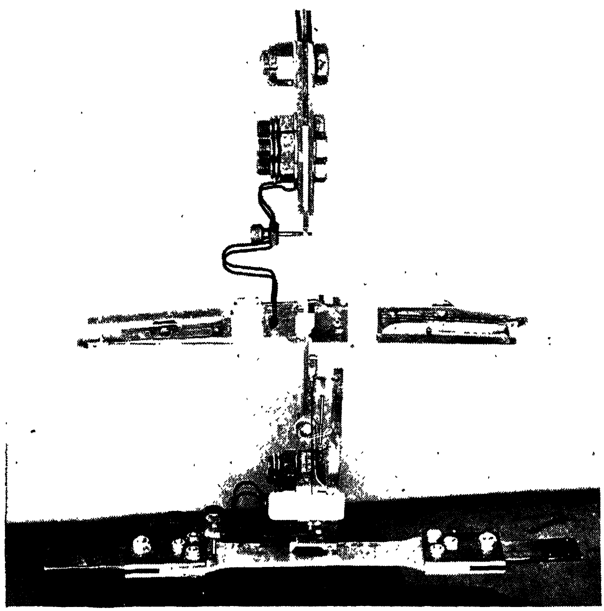


FIG. 15.—Methods of attaching Huggenberger tensometers to tensile calibration coupons.

A similar series of resistance wire strain gauges have been under development for several years by the Consolidated Aircraft Corporation and are more familiarly known as "Celstrain" gauges. The early practical Celstrain gauges are discussed in Reference 20 (1940) in their application to plate-stringer and shear specimens. These early C-1 Celstrains weighed approximately 0.125 oz. each and were experimentally used, in a $2\frac{1}{2}$ by $\frac{1}{2}$ by $\frac{1}{4}$ in. size of approximately 22 ohms resistance, with considerable success.

The present type of Celstrain extensometer has been simplified to a basic paper base, a grid of resistance wire, and attaching cement. These Types C-3 Celstrains consist of approximately $4\frac{3}{4}$ in. of 0.0015-in.-diameter (1.5 mil) "Advance" wire, jig-assembled in four strands in a 1-in.-long by $\frac{3}{32}$-in.-wide test area and insulated above and below with tissue paper. These filament Celstrains, weighing only 0.008 oz., need only be cemented flat to the test specimen with commercially available methyl-

Fig. 16.—Technician assembling Celstrain gauges.

methacrylate cement, and after drying overnight (or 2 hours under accelerated drying conditions by use of a warm air blower) they are ready for use. Since Type C-3 Celstrains may be trimmed down to a width of $\frac{3}{16}$ in., they are readily adaptable to corner stress concentration measurements, can be laid in corner radii, or spotted between rivet rows on spar flanges, etc.

Women technicians, inexperienced in delicate instrument manufacture, have been trained in 2 weeks to assemble Type C-3 Celstrain gauges in sufficient quantities to bring the complete unit gauge cost to approximately 20 cents. Since this new type of wafer-thin gauge is so inexpensive, its use but once is justified, and it may be discarded with the failed test specimen.

Figure 16 shows a woman technician assembling Celstrain gauges. Inasmuch as 100 or more gauges may be placed on an experimental wing during static test, the assembly of such gauges in quantity must be placed on a production basis, assembly jigs, driers, and potentiometer resistance control being used.

The Celstrain indicating apparatus, shown in Fig. 17, has proved very sturdy and practical in research and experimental testing. This setup, made for a static wing test, provided a

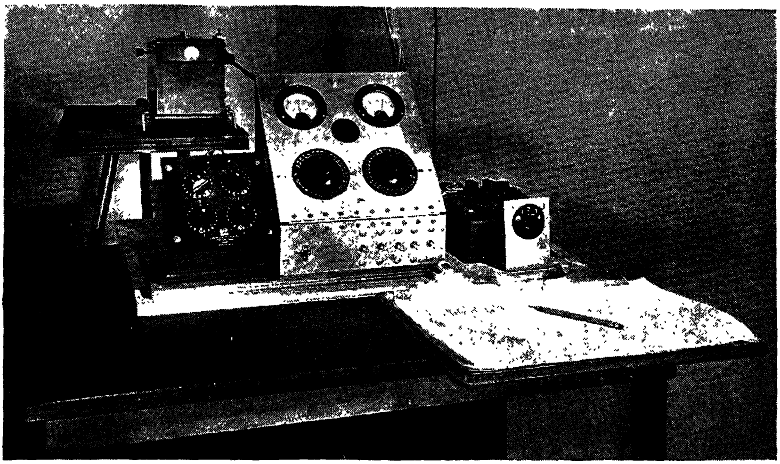


FIG. 17.—Celstrain gauge indicators.

means of reading 60 Celstrains in less than 8 min. per load increment.

The heart of the Celstrain indicator is the light-beam galvanometer shown in the upper left-hand corner of Fig. 17, mounted on a pedestal independent of the remainder of the apparatus. A simple Wheatstone bridge circuit is used in which the various mounted Celstrain gauges are progressively placed in the "unknown leg" of the circuit and the readings taken from the galvanometer directly. The null-point method of reading consumes more time, without added accuracy. A "dummy" Celstrain is placed in the "leg" opposite that of the loaded Celstrain. Equal lengths of No. 16 to 18 copper wire connect the temperature-compensating dummy and the Celstrains to the two 30-point selector switches. Thus ordinary temperature variations during the test period will affect both

gauge and compensator alike, and the Wheatstone bridge will be relatively unaffected.

Figure 18 shows a typical Celstrain gauge installation on a pressure cylinder representing a scale specimen of a pressure cabin. In instances where the gauges are cemented on relatively

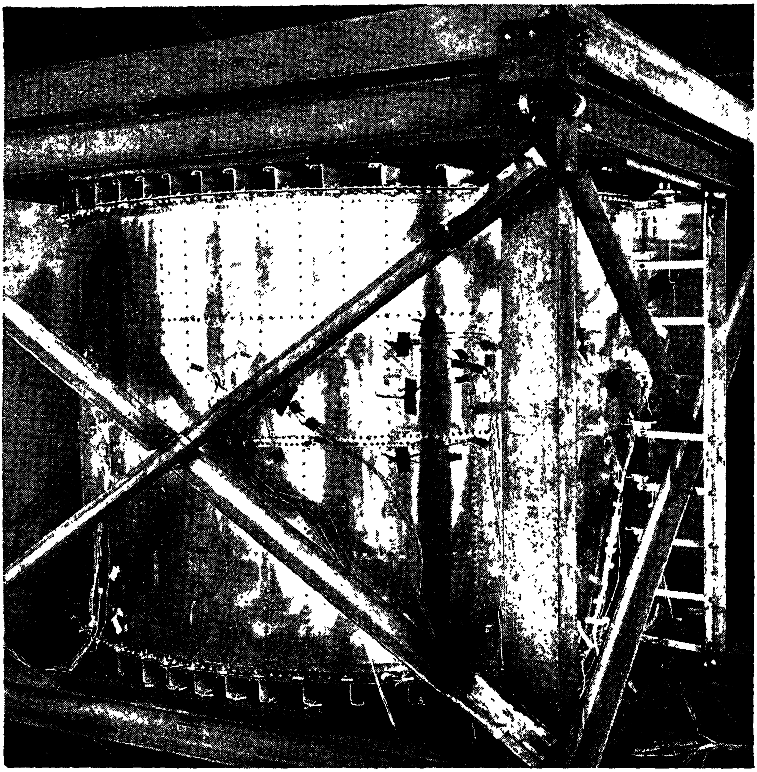


FIG. 18.—Application of Celstrain gauges to a pressurized fuselage section.

thin, unsupported sheet, one gauge on each side of the sheet has been found necessary. These Celstrains may be read separately to calculate the amount of bending and axial stress present, or they may be connected in series, thus nullifying the bending stresses and indicating only the axial tension or compression stresses. On heavy sheet or on stringers, angles, flanges, etc., only one Celstrain is necessary if secondary bending is not a sizable factor. Gauges mounted in series on a test specimen

have also been used to obtain directly the average strain across the section.

The resetting of the pointer on the Huggenberger Tensometer is inconvenient, takes time, and may lead to errors. No such resetting is necessary on Celstrain gauges, since a choice of sensitivities covering full-scale deflection on the light-beam galvanometer can be made by the use of one of the switches in the lower right corner of the indicator unit shown in Fig. 17. The 25-min. deflection of the light beam to the left (indicating tension) or the right (indicating compression) of the center line may be chosen for Type C-3 Celstrains mounted on 24ST aluminum alloy at 3 volts direct current as 10,000 lb. per sq. in. on high sensitivity, 40,000 lb. per sq. in. on intermediate, and 60,000 lb. per sq. in. on low sensitivity. Inasmuch as the galvanometer scale can be read to 0.1-mm. increments, it is possible to read "indicator" stresses to 50 lb. per sq. in. The experimental error in applying gauges, reading the galvanometer, thermal drift, spot-check calibrations of mass-production lots of gauges, etc., makes the stress indications subject to ± 5 per cent variation, an accuracy comparable with most mechanical-strain gauges without the remote reading advantages.

Inasmuch as the wire-resistance strain gauge has such infinite varieties of applications to the test engineer's problems and since heretofore very little has been published on the detailed use and operation of the Celstrain type gauges (see Refs. 20 and 21), a little more information may not be out of place at this point.

After the Celstrain gauges have been cemented on the test specimen (Fig. 18), usually parallel to the principal stress direction, and have thoroughly dried, the 5- to 100-ft.-long wires are connected to binding posts on the rear of the indicator shown in Fig. 17. The dummy unstressed Celstrain gauge is placed in the approximate vicinity of the majority of stressed gauges, to be influenced by any thermal effects there present. Zero balance is obtained by progressively switching in each of the Celstrain gauges on the unloaded test specimen and balancing each unit to zero galvanometer deflection by adjustment of the four-knob decade box. These zero readings for each gauge are recorded. After a load increment has been applied and maintained in equilibrium, each gauge, in turn, is set at its zero reading on the decade box and the galvanometer deflection, in plus or minus

millimeters, is recorded. As before stated, three operators on the Celstrain indicator, with a little experience and teamwork, can comfortably read 60 gauge combinations in 8 minutes.

The galvanometer readings are later plotted vs. load to give straight lines, if below the material yield point and without local bending, or plotted as curves, if yielding or bending of the material is taking place. The slope of the plotted points, when connected to zero and multiplied by the sensitivity constant, will give the actual stress in the specimen at any desired load increment.

The uses of this type of wafer gauge, with negligible inertia and weight, relative insensitivity to temperature changes, immunity to vibration effects, low initial cost of Celstrain indicator and replacement cost of individual gauges, and remote-indicating possibilities, are astounding. When the price of $200 for a 30 Celstrain gauge indicator, complete with gauges, batteries, switches, etc., and ready for use, is compared with other remote-indication gauges of ten times the cost and with no more dependability or accuracy; the reader may realize the future awaiting the Celstrain type extensometer.

Celstrain gauges are equally satisfactory for the measurement of dynamic or static stresses and strains. Vibration tests of Celstrain gauges, affixed at the root of cantilevered aluminum-alloy beams, at frequencies of zero to over 10,000 cycles per min. have demonstrated that these gauges are capable of reasonably accurate indications of dynamic strains without loss of bond.

A few of the more common uses of Celstrain gauges in the aircraft field are as follows:

Weighing loads or forces to fractions of an ounce.

Measuring hydropress rubber pressures simultaneously in three dimensions.

Checking stresses (static and dynamic) on aircraft in flight or at rest on the ground.

Measuring bolt loads in structural splices.

Recording impact loads (even at high frequency).

Measuring control cable loads, etc.

Application of Hydraulic Loading Units to Aircraft Testing.—Until a few years ago the average test engineer considered sand-bag loading and the use of turnbuckles and weighted platforms as the standard method of load application in the static testing of

aircraft structures. The trend today is toward the use of hydraulic jacks and rams wherever possible. The emphasis is on calibrated hydraulic gauges, rather than on dynamometers or scales for load-measuring devices. This change of thought in load application and load measurement in structural tests has already had far-reaching effects in such operations as full-scale wing testing.

Jackman (Ref. 19) describes the testing of large airplane wings by the old sandbag method vs. the newer hydraulic method. The latter, though somewhat more expensive in initial cost, is nevertheless more desirable in ultimate load tests because

1. Better load control is possible at all times.
2. Loads may be applied to the structure for short intervals of time.
3. Hydraulic loading permits the removal of the load between increments, if desired, to check for permanent set.
4. Remote application of loads and reading of deflections and Celstrain gauges make the personnel safety factor much better.
5. Hydraulic methods lack the danger of shock or impact loads that are present during the loading of large structures by sand or lead.
6. The number of test personnel may be approximately one-tenth that required in sand loading.
7. Both surfaces of the wing structure are visible in the hydraulic system for inspection but covered in the sand- or lead-loading methods.

The sandproof-loading method on large aircraft wings of 110-ft. spans has several times been successfully applied by the test personnel of one aircraft corporation. A typical example of such a wing-proof test performed several years ago is shown in Fig. 19. In this instance the wing was hung by its four fittings from a steel jig structure approximately 10 ft. above the floor. Prior to the installation of the wing in its test position, a wood loading platform had been constructed adjacent to the test jig to carry the 60 tons of sandbags. This load platform alone contained sufficient lumber to build four wood frame houses.

The sandbag increments were laid out in rows on the platform and at the time of the test were transferred by a well-trained crew to a corresponding position on the wing surface. The general procedure for a sand-loaded proof test can be so standard-

ized that the time intervals for each load increment can be closely predicted. The application of the proof load to the wing shown in Fig. 19 took approximately 3 hr., with over 50 men trained, each for a particular duty, on the day of the final test.

Contrast with the above-mentioned sand-loading wing test method the Hydrotest method of completely hydraulic loading and control developed by and used at the same company on two full-span wings. The use of sandbag loading may be efficient and practical for the proof loading of wings, but the advent of high-wing loadings on highly tapered wings makes some more con-

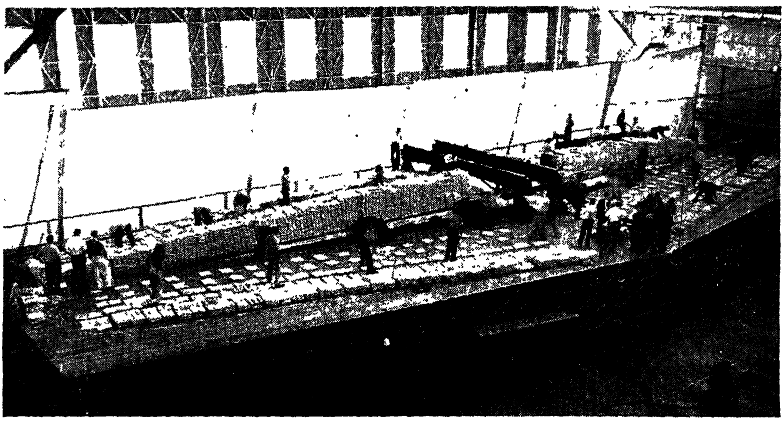


FIG. 19.—Proof static test of large cantilever metal wing using sand bags.

trollable test method necessary for destruction tests. The instability of towering piles of sandbags, especially near the sloping deflected wing tips, and the desire to protect both test personnel and valuable wing structure from injury caused the test laboratory to design a novel hydraulic loading method, now commonly known as the "Hydrotest" system.

This method has, in the last year, been applied to two of the largest destruction wing-test setups in the history of aviation in the United States. Sections of larger wings have been tested, but the two all-metal wings, with more than 110 ft. of span and a wing loading in one case of over 40 lb. per sq. ft. of surface, constitute probably the most massive wing-test projects to date.

The testing method appears at first glance to be complicated, but it actually reduces into several surprisingly simple units. The primary structure consists of the wing-supporting structure.

Figure 20 shows an end view of an inverted wing under 80 per cent of the low angle-of-attack design condition. Inasmuch as this wing is an integral part of the fuselage on a midwing airplane, a full-scale portion of the fuselage was duplicated between heavy steel end plates supported on a steel substructure at a sufficient height above the concrete floor to allow over 50 in. of wing-tip deflection.

The wing was tested in two positions—upright and inverted—so as adequately to demonstrate its strength under two simulated critical flight conditions.

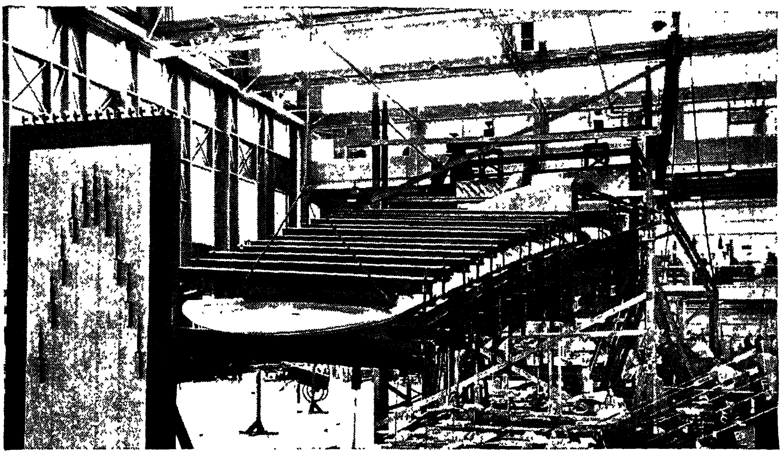


FIG. 20.—Wing undergoing proof test by "Hydrotest" method.

The air load was applied to the wing through rubber-covered, wood formers clamped at wing-bulkhead locations. These formers, as shown in Fig. 21, were grouped in twos or threes by spreader bars and attached to fore and aft loading beams. The loading cables were attached to a predetermined position on the lower beams so as to give the correct chordwise load distribution. The cables passed down to the steel floor structure, around ball-bearing steel pulleys, and forward to the end of a system of levers, actuated by hydraulic rams. The correct chord-beam ratio of the air load in each test condition was regulated by the angle of pull of the load cables from the wing.

Two or more rams actuated each loading lever through a common pressure system, as shown in Fig. 21. More than 40 such rams were used on each test, controls being obtained by load

dynamometers placed in the cable systems at several check points. The common pressure could thus be applied to the whole wing by one operator turning a single valve on a motor-driven pump.

The main difficulty of the Hydrotest development proved to be the design difficulties encountered in high-pressure hydraulic systems, since the desired 2,500 lb. per sq. in. is, even today, considerably above conventional hydraulic practice. Proven

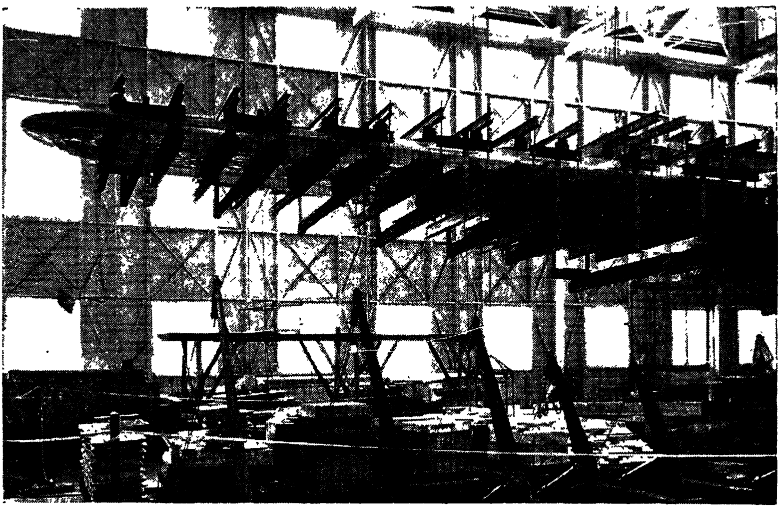


FIG. 21.—Typical "Hydrotest" installation on a large cantilever metal wing.

equipment for such tests was not readily available from the aircraft accessory manufacturers. The test laboratory therefore set about solving this difficulty and after repeated tests on experimental equipment finally developed a static-test hydraulic system, using commercial "snowplow" equipment, capable of pressures well over 4,000 lb. per sq. in.

The heart of the Hydrotest system is the control unit, with its motor-driven pump, oil reservoir, accumulator, valves, etc. With this "finger" control, one operator can apply a 20 per cent load increment to both semispans in 2 min., a marked contrast to the 15-min. loading schedule of the 12 two-man teams in the conventional sand-loaded systems.

Two other pressure systems were loaded simultaneously with the air-load hydraulic system, each by one operator. The

nacelle uploads were manually pump-applied by one hydraulic ram per engine mount, on a four-nacelle pressure system. The fuel in the tested wings was carried in integral wing tanks. The difference between the fuel load and the air load over the fuel-tank area was applied upward either by an air-inflated rubber bag covering the tank area or by wing formers uploaded by hydraulic rams on a manually operated pump.

To prevent the steel-beam floor structure's rising under the cable loads, heavy drop-hammer dies and lead ingots from the foundry department were borrowed for use as dead weight. No lag screws or massive hold-down bolts were used between the floor beams and the cement floor. The test structure could thus be removed from the testing floor within a relatively few hours after the completion of the static test. Inasmuch as specially prepared flooring, with submerged concrete beams and steel eyebolts, is not necessary for the Hydrotest system, large static tests can quickly be set up and torn down in any convenient space.

The Hydrotest system, when applied to static wing tests, can reduce destruction test time to one-quarter of that required by sand-load methods, requires 5 to 10 test personnel instead of the latter's 50 to 60, and provides a safer, more versatile, and more controllable test system for the aircraft industry.

Measurement of Structural Deflections.—The old method of measuring deflections in test structures under static loading by means of levels and stadia rods is also being superseded by more efficient modern methods. The height of test structures above the floor, the frequent lack of vision in under-wing areas, and the possibility of the accidental motion of the level tripod at a critical time of the static test have caused more trustworthy deflection measuring schemes to be considered. A simple method, used in areas where there is no danger to the recording personnel, makes use of hanging weighted scales passing between fine parallel wires in individual floor stands, thus allowing deflection reading to be made to $\frac{1}{100}$-in. increments. A slightly more complicated but much more convenient method of measuring wing deflections is shown on the "deflection board" of Fig. 20. This remote-indicating system makes use of 10 fine wires attached to various spar locations on each semispan, each threaded under and over three small ball-bearing pulleys to

weighted indicators moving over a graduated vertical chart. A deflection board at each wing tip, serviced by a reader and a recorder, makes it possible to record the deflections at 20 to 30 stations on a test wing, readable in $\frac{1}{100}$-in. increments, in 2 min., and with no danger to personnel.

CHEMICAL AND PHYSICAL TESTS

Raw-material Analysis.—The major portion of the routine analytical work performed in the chemical and physical laboratories consists in the analysis of various materials that are used in the planes and that are purchased under Army and Navy specifications of physical properties and composition. During the present period of rapid expansion, the manufacturers of the material used in aircraft lack experienced inspectors, and many mix-ups occur in the tagging and shipping of raw stock.

Material or item	Chemical analysis	Physical test
Chrome-molybdenum forgings	Yes	Yes
Chrome-molybdenum sheets and tubes	Yes	No
Chrome-molybdenum bars	Yes	Yes
Chrome-molybdenum castings	Yes	Yes
Welding rods (all kinds)	Yes	No
Stainless castings	Yes	Yes
Stainless sheets, tubes, and bars	Yes	No
Stainless M-286 steels	Yes	No
Carbon and nickel steels	No	No
Aluminum-alloy castings	No	Yes
Aluminum-alloy forgings	No	Yes
Die castings	No	Yes
Cables	No	Yes
Gray iron castings	No	Yes
Brass and bronze castings	Yes	Yes
Brass and bronze bars	Yes	Yes
Magnesium-alloy castings	No	Yes
Rivet wire	No	Yes (after heat-treatment)
Cords, ropes, and belts	No	Yes
Springs	No	Yes
Fabrics	Occasional	Yes
Electric cables	No	Yes
Solders	Occasional	No

Some raw materials are source-inspected by government personnel. It is usual to check-test only occasional samples from such sources. Materials not source-inspected or stock from questionable purchased lots are checked for compliance with the strict service specifications.

The table on page 244, indicates the usual tests made in one aircraft chemical and physical laboratory on incoming raw material.

As a typical example of the detailed steps that a chemist must consider in the routine determination of the "points" of carbon (C) in a submitted steel sample, we shall now let the chemist in charge of a typical aircraft chemical laboratory tell his story:

The operations performed are of comparative simplicity, but care and patience must be exercised to secure good results. Thus a little dust or grease on one's hands or in the chips, a slight leak in connections, or inaccuracy at the balance would cause erroneous results. Briefly, the steel chips are weighed, placed in the boat and inserted in the quartz tube which is heated to 1,800°F. A stream of oxygen is passed through the tube which causes the steel chips to burn to an oxide (Fe_3O_4) while the carbon is converted into carbon dioxide (CO_2), which passes through the tube with the excess oxygen. This CO_2 gas is absorbed in a midvale bulb while the oxygen passes on. The absorbent consists of Askarite, a soda lime and asbestos mixture. The soda lime (Na_2O) unites with the CO_2 gas, forming sodium carbonate (Na_2CO_2), thus increasing the weight of the midvale bulb. This bulb is weighed prior to the determination and again after it is completed (10 min.) and the increase in weight noted. As the percentage of carbon in CO_2 gas is $\frac{12}{44}$ or 27.27 per cent of the weight obtained, the amount of carbon can be readily estimated. To facilitate calculations, a factor weight of 1.3636 grams of steel is used. The increase in weight then becomes just double the percentage of carbon, and the carbon percentage is obtained directly by dividing by 2. Inasmuch as one-millionth of a pound on the balance is equivalent to one point of carbon, one can readily see why extensive precautions must be taken.

Control of Shop-process Tanks.—Many shop processes are dependent, for uniformly good results, upon the solution control maintained by the chemical laboratory. Periodic samples are removed from all critical solution tanks in the factory, carefully analyzed, and recommendations made for material additions, if found necessary.

Anodic-treatment Tanks.—The percentage of chromic acid used as the electrolyte in the anodic process is controlled with the use of a Beckman pH meter. Daily samples are brought to the laboratory for analysis. Past experience has shown that a solution maintained at approximately 2.00 pH (in a 1/50 concentration) gives satisfactory anodic film with the specified time and voltage. Daily additions of chromic acid are made to maintain this pH reading.

The cleaning tanks, in which the aluminum-alloy parts are cleaned from oil and paint prior to anodizing, are tested daily by the pH method.

Control of Heat-treatment Tanks.—Some corrosion troubles following the sodium and potassium nitrate heat-treatment baths for aluminum alloys are the result of lack of chemical control of the molten salt. Biweekly samples from each nitrate bath in the factory are tested for alkalinity by means of pH tests. Periodic corrections are recommended by the chemists in the form of potassium dichromate additions.

Plating Baths.—The sodium cyanide solutions used in the cadmium-plating operations in the factory are periodically tested by the chemists, in addition to the tests performed by the plating operator. These laboratory tests include the estimation of free cyanide, total cyanides, total alkali, and carbonates.

Other Functional Duties of Chemists.—Besides the routine and daily tests mentioned above, the chemists and physical test engineers are responsible for a variety of operations.

Welder Tests.—The Army and Navy require that all welders working on steel structures entering service airplanes pass a qualifying welding test on admittance to the factory and at 6-month intervals thereafter. A complete test of a welder includes the following specimens:

3 to 5 V flat butt welds
4 tubular butt welds (2 horizontal, 2 vertical)
2 crosses
2 cluster welds

These welded specimens are tested in the laboratory, with Army and Navy inspectors as witnesses. The cluster welds are later sawed through the center, polished and etched, and inspected

for the quality of work and weld penetration. Welders passing this test are given papers qualifying them for service welding.

Cable Tests.—Sample swaged cable terminals, conforming to engineering drawings and inspection requirements attached to cables, are tested in the laboratory to failure.

Calibration of Shop Scales.—The dynamometers and spring scales used in the factory are periodically tested and adjusted.

Miscellaneous Tests.—Gasoline, oil, and greases are frequently tested for quality and purity. Unknown materials are submitted for analysis.

Manufacture of Factory Solutions, etc.—The chemists must periodically replenish solutions or materials used by the factory, such as

Antiscaling compound for steel heat-treatment
Antiseize compound to prevent corrosion at threaded joints
Litharge compound to ensure tight joints
Special soldering pastes and fluxes, etc.

Report Routine and Procedure Control.—No test requests are required on the routine materials submitted periodically to the chemical laboratory for analysis. All special tests, however, are required to be covered by the standard test request described earlier in this chapter.

The typical report form, shown in Fig. 10, is completed for all physical and chemical tests, no matter how trivial, so as to record all laboratory work.

The routine chemical testing procedure used in the laboratory is written up on standard tests and kept up to date on unusual tests as they are made. This procedure manual is of special value to an inexperienced chemist in his first weeks in the laboratory.

METALLURGICAL CONTROL

Purposes.—The reasons for the existence of the four or five personnel in the metallurgical group and the photomicrographic laboratory are three:

1. To control or recommend action on the metallurgical functions of factory processes such as

a. Chemical content of metals affecting heat-treatment, drawing, rolling, bending, etc.

b. Temperature and time elements in heat-treatment.

c. Hardness troubles arising in shop materials, etc.

2. To investigate the metallurgical aspects of new or substitute metals.

3. To carry on research in metallurgical phases of aircraft manufacture.

Control Methods and Paper Work.—This group, as in all the diverse groups in the engineering test laboratory, must be covered by an authorized test request prior to starting any investigation. In the paper work of this group it is especially important that a detailed description be presented by the originator of the metallurgical request of the history of the case, the samples, and the desired test results.

After receipt of the specimen and all information pertaining thereto, it is assigned the next consecutive number from the notebook Metallographic Record. All information received is transferred to this notebook. The following is a typical entry:

Metallographic No.	Reference No.	Type of metal	Date received	From whom received	Photomicrograph	Investigation
181	Heat X-4424	M-286 (AISI-431)	8/28	M.E.T.	8/28 (*a,b*)	Determine the quantity, size, and direction of ferrite Make photograph

Metallographic No.	Date finished	Observation	Remarks
181	8/29	Approximately 25 per cent fine ferrite in a martensitic matrix. Ferrite is in stringers parallel to the major axis of the bar	R_c = 38. Izod = 64 ft.-lb.

FIG. 22.—Sample entry, Metallographic Record.

Cards, similar to that shown in Fig. 23, are written for each specimen examined and are filed under various headings in the cross index of the Metallographic Record.

Cards, similar to that shown in Fig. 24, are written for each photograph taken, the photograph is mounted on the card, and the card is filed numerically in the metallographic-specimen file.

Photomicrography and -macrography.—On receipt of the specimen it will, as a rule, be explained what type of investigation

Material Control No. Heat No. X-4424 Heat-treatment Department

Date ______________ S.A.E. M-286 (AISI-#431)

Material		Analysis	
181—8/28/41 P.M. (*a*, *b*)	Rod	C	0.12
	Bar	Cr	16.88
	Tubing	Mo	
	Forging	Ni	1.90
	Casting	Mn	
	Sheet	Va	

FIG. 23.—Metallographic Record.

No. 181*a* Metallographic Laboratory

Kind of material: M-286 (AISI-431)	Magnification: 250
Etchant: Marble's	Time: 10 sec.

Chemical Analysis

%Fe	%C	%Cr	%Ni	%Mo					
	0.12	16.88	1.90						
%Al	%Cu	%Mg	%Mn						

Remarks: Heat X-4424

Izod = 64 ft.-lb. *Rc* = 38

Cross Section

Structure: Approximately 25 per cent fine ferrite in a martensitic matrix —parallel to axis of bar. Shows cross section of ferrite stringers.

Grain size No. 5½.

Photo-
micrograph
to be
mounted
here

FIG. 24.—Metallographic photograph.

is to be made, and from this it is usually possible to determine how the specimen is to be sectioned and whether a micro- or macrophotograph is desired.

Apparatus and Specimen Preparation.—The specimens are first sectioned in the shop or on the laboratory disk saw. After sectioning, the pieces are filed as smooth as possible, being kept flat at all times.

All specimens are mounted in transparent Lucite by means of a special hydraulic mounting press. Each mounted specimen is permanently numbered.

The mounted specimens are next polished on six grades of emery paper in the following order: Nos. 280, 320, 400, 2 zero, 3 zero, and 4 zero.

The specimens are next polished on a circular polishing wheel, levigated alumina being used as an abrasive. Final polish is obtained on a second lap, magnesium oxide in water being used.

After the final polish, if the specimen is sufficiently free of scratches, it is etched.

The specimen is then inspected on the Bausch and Lomb metallograph at magnifications of 25 to 500, as desired.

Interpretation.—The diagnosis of metallurgical troubles from photomicrographs or -macrographs should be done only by trained metallurgists, since the educational background required for such work is not readily obtainable by a beginner in the laboratory.

SPECTROGRAPHIC ANALYSIS

In many instances of material-composition analysis in airplane factories, there arise occasions when the submitted samples are too small for a wet chemical analysis by the chemical laboratory. The use of the spectrograph is becoming more common in analyzing these samples.

Purpose.—Some reasons for the existence of a spectrographic laboratory in an industrial institution are

1. Analysis of small quantities of the unknown material.
2. Saving of time over the wet chemical method.
3. Quick check for presence of several suspected elements.
4. Separation of elements not readily analyzed by wet chemical means (*i.e.*, sodium and potassium).

Apparatus and Procedure.—Figure 4 shows a simple spectrographic laboratory in an aircraft company. The Cenco concave replica grating spectrograph shown on the left cabinet has many times proved useful in qualitative analysis of unknown samples and, in a few instances, has been used in approximate quantitative analysis of some of the simpler spectrograms of aircraft materials.

The apparatus has been used with both direct-current arc on 160 volts generated by a motor generator set and high-voltage alternating-current spark.

The details of spectrographic procedure may be obtained from Brode (Ref. 18).

Interpretation and Limitations.—Here again, as in photomicrography, the beginner has little chance of interpreting a spectrogram, without thorough education and experience in the subject.

The spectrograph is not a cure-all for all chemical problems, however, since carbon, phosphorus, sulphur, and a few metals may have very complicated spectra and their analyses are somewhat laborious and probably too lengthy for ordinary laboratory procedure.

HIGH-ALTITUDE LABORATORY

Nearly every large aeronautical company that is designing or expects to design planes capable of operating at high altitudes is considering tests of personnel and equipment in an evacuated chamber, at low temperatures. Several high-altitude chambers have been functioning for several years, and the lessons learned in these early tests have been applied to chambers now being designed and built.

Purpose.—The primary purpose of a high-altitude laboratory is, of course, to study the personnel and operational equipment under conditions simulating the upper air. The indoctrination of flight personnel, prior to their test flights to high altitudes in the test airplanes, is readily performed in the chamber under controlled conditions.

Test Apparatus.—The high-altitude apparatus used in the various aircraft companies will differ to suit the individual needs of the local test organization. The following description of test apparatus used in a particular high-altitude laboratory is typical of test equipment in the aircraft industry.

Figure 25 shows the high-altitude laboratory floor plans. The Alti-Chamber, a two-compartment steel cylinder equipped for vacuum and temperature controlled conditions, is shown at the

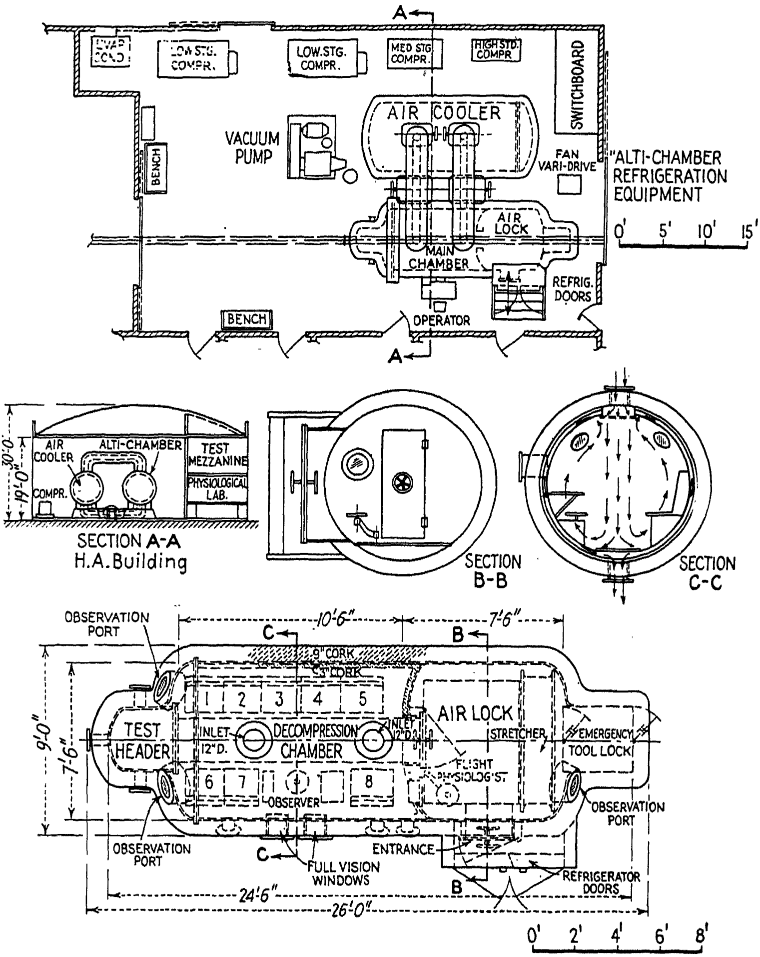


FIG. 25.—Layout of high-altitude test laboratory.

upper end of the building. To the left of the Alti-Chamber are the "air-cooler" tank, closely resembling the former in size and shape, and the remainder of the elaborate refrigeration equipment.

Figures 25 and 26 present some of the design problems involved in constructing an Alti-Chamber for near vacuum and $-80°F$.

temperature conditions. The $\frac{1}{2}$-in. thick steel shell, divided into an air lock and a main decompression chamber, must be insulated with 12 in. of cork in such a way as to permit vision, access doors, and the attachment of regulation equipment. The photograph was taken during the construction of the laboratory, to show the tank structure that later was covered with insulation. The Alti-Chamber is provided with three doors; the main 60- by 24-in. entrance into the air lock; a similar 60- by

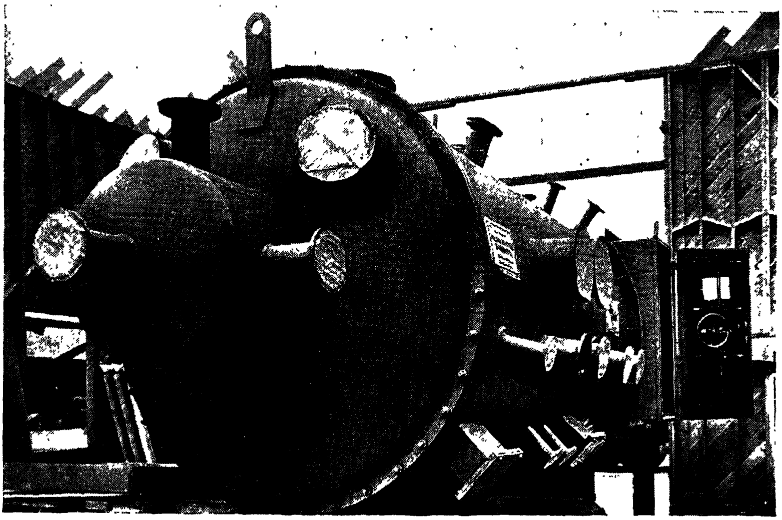


FIG. 26.—Alti-Chamber—shell prior to installation of insulation.

24-in. door between the air lock and main chamber; and a semicircular emergency exit from the air lock.

The Alti-Chamber operator sits outside the tank at a control panel, but he can both see the occupants through a wide-angle lens and communicate with them through an interphone system. A two-disk recorder monitors all conversation over the interphone system, thereby maintaining a permanent record of personnel observations and test sequence.

Provision is made in the Alti-Chamber for two trained observers, a flight physiologist in the air lock, and an observer riding with the crew undergoing indoctrination in the main chamber. Close to each of these experienced observers are control valves and switches through which the tank may be

Engineering Test Laboratory

Flight Log

Test Order No. 4-320-1 W.O. 295

Name of Test: Calibration of flowmeters (Heidbrink)

Plan: At altitudes (30,000 feet, 35,000 feet, 40,000 feet) measure delivery of flowmeters, kinetic type.

Alti-Chamber

Date May 3, 1942

Barometer 759.1 mm. Hg

Room Temperature 23°C.

Operator R. J. C.

Test Engineer L. Jones

Subject	Mask type	Regulator type	Flow	Communication	Denitrogenation symptoms: Exercise	Time	1	2	3
1. L. Jones	A-8	H	×	×	Mild	45 min.			
2. F. Johnson	A-8	H	×	×	None	None			×
3.									
4.									
5.									
6.									
7.									
8.									
Observer J. Brown	A-8	H	×	×	Mild	45 min.			
Observer									
Observer									

1 Anoxia 2. Pain (ear, etc.) 3. Aeroemphysema (the bends, etc.)

Oxygen-system Check
Pressure (main supply): 1,000 lb.
Pressure (reserve supply): 1,800 lb.
Emergency No. $\boxed{3}$
Mask Type $\boxed{\text{A-8}}$ 500 lb.

Altimeter Check
Last calibration: 5/1/42
Aneroid set at 759.1 mm. Hg
Mercury set at 759.1 mm. Hg
Safety Valve set at 41,000 ft.
Signed:
L. Jones
Observer in Charge

Time	Altitude (ft.)	Temperature	Oxygen flow	Remarks	Recording No.
10:00 A.M.	0	23°C.	0		
10:10 A.M.	30,000	22°C.	30,000	Delivery *A.* 8.8 L. per min. *B.* 9 L. per min.	
				C. 8.6 L. per min.	
10:35 A.M.	35,000		35,000	Delivery *A.* 15 L. per min. *B.* 16 liter per min.	
				C. 16 L. per min.	
10:40	35,000	22°C.		2 has pain right knee	
10:45	35,000			Pain worse	
10:47	30,000			Pain relieved	
14:55	0				

FIG. 27.—Flight log (high-altitude laboratory).

quickly "bled" to atmospheric pressures in cases of emergency. All entrance doors are of the quick-acting type, allowing operation from either side.

Test Procedures.—The operation of the Alti-Chamber is under the engineer in charge, who in turn is responsible to the flight physiologist for crew-indoctrination tests and to the chief test engineer for equipment or structural tests performed in the laboratory, as shown in Fig. 1. The crew check tests are made to approximately 30,000 or 35,000 ft. in an effort to train flight test personnel in the proper use of oxygen equipment and "bail-out" equipment and in the emergency treatment of fellow crew members. Those of the flight personnel who are unusually susceptible to decompression sickness (aeroemphysema, or "the bends"), who cannot clear their ears in descents, or who have other difficulties can be discovered easily by these tank tests. Where possible, further trouble will then be prevented by appropriate methods, or the persons will be limited to lower altitudes.

During the indoctrination tests of flight crews, close supervision is maintained of each person by the flight physiologist through a flight log. A typical test run in the Alti-Chamber is shown in Fig. 27.

INSTRUMENTATION TEST GROUP

Purpose.—This small group of test engineers are essentially shop-contact men and women whose responsibility it is to design, install, calibrate, and operate flight test equipment in experimental airplanes.

Duties.—Each instrumentation engineer is assigned to an airplane, alone or with a fellow engineer, and is responsible for the adjustment and maintenance of the experimental and flights instruments in that plane. He must be of flying status and capable of taking flights to 30,000 ft. and must bring back the necessary test records, which, when transcribed by the woman technicians trained in this work, will provide valuable data for the aerodynamics and flight test group.

Installations.—Prior to the instrumentation of an airplane, the instrumentation engineer should "mock up" the test equipment in wood in the airplane, if one is available, it thus being possible to make studies of vision, clearances, and operational difficulties.

After acceptance of the mock-up version by the project engineer, the instrument engineer should release drawings to the shop covering each instrument, tubing, wire, and thermocouple installation. He then is responsible for the proper operation of these parts when built and installed in the actual airplane. At frequent intervals, he should calibrate all important flight instruments on his plane against accepted standards.

The instrumentation of an airplane should start many months before the anticipated flight date, since the installation of the test equipment should be done by the shop at the most convenient assembly time for each airplane part. Thus the 8,000 ft. of manometer tubing or the 5,000 ft. of glass-insulated iron-constantan thermocouple wire on a modern four-engine plane should be released to the shop mechanics in sufficient time to be threaded into the wing leading edges prior to their closure.

MISCELLANEOUS TESTS

Corrosion and Salt-spray Tests.—Inasmuch as aircraft are built of highly corrosive aluminum-alloy material (until adequately protected) and operate, in the case of seaplanes and flying boats, from highly corrosive mediums, it is not strange that corrosion tests should take much of the test engineer's time.

Aside from a knowledge of the basic principles of electrolytic action of dissimilar metals, the most satisfactory method of judging the merits of a particular design or paint finish, from the corrosion angle, is to subject test samples, prepared exactly like the basic structure, to accelerated salt-spray action. This is frequently done in a specially prepared tank, maintained at 95°F., in a dense fog of a 20 per cent sodium chloride solution. The samples are exposed to this atmosphere for days, weeks, or months, depending on the material and surface finish, and the results judged by comparison of corrosion and physical properties with control specimens. Samples are also subjected to atmospheric and marine exposures under controlled conditions.

High-speed Action Tests.—From time to time, every test laboratory is asked to check the action of moving parts and interpret the results. In most cases the use of a slow-motion camera, with the subsequent analysis of each frame of the film for change of position, velocity, acceleration, etc., has proved

very satisfactory. The author has used a camera at 128 frames per second in the analyses of the motion of a drop hammer, a pile driver, and even the landing action of airplanes, studies of tire deflections, brake actions, etc.

Low-temperature Tests.—The demand for high-altitude bombers and transports is changing this phase of the test engineer's work from room temperatures to subzero surroundings. Inasmuch as each test laboratory has developed or had built for it special low-temperature chambers in which to perform high-altitude tests, no blanket coverage of the equipment used by all aircraft companies can be attempted here. Instead, the equipment used by one large aircraft corporation will be described in some detail.

The boxes used for "cold-room" testing were designed and built by the company of wood construction with walls 12 in. thick. Between the inner and outer sections of the walls is a 10-in. wall of Fiber glass. The surfaces of the walls are asphalted, and the outside has a coat of aluminum paint.

The three boxes will handle tests of 6 by 6 by 9 ft., 3 by 3 by 4 ft., and 2 by 2 by 2 ft. The two larger boxes are operated from the same Dry Ice "secondary-refrigeration" unit, and the smallest box is cooled by direct immersion of Dry Ice cubes into the testing area.

The refrigeration unit for the larger boxes consists of a series of tanks into which are put Dry Ice and alcohol. This is a secondary system of cooling that operates economically at satisfactory temperatures. The large box, partitioned to a 6- by 6- by 6-ft. test compartment, can be cooled from +40 to −80°F. in 8 hr. A 1,000-lb. charge of Dry Ice is put into the unit and about 400 lb. are used up in cooling the boxes to −80°F. About 15 lb. of Dry Ice are used each hour in keeping the temperature at that level during an average test run.

The cold rooms are used entirely for experimental and development parts. Both material and functional units are tested. Plastics receive cold-room tests, as do windows and doors. Many parts are given pressure and cold tests at the same time.

It is expected that production parts will soon be put through cold tests, and plans are being made to develop the present equipment for that work. Under consideration is a primary system of cooling to increase the speed to temperature drop.

The system of cold testing as used at this corporation has been very satisfactory, and the temperatures reached have been adequate. As well as being economical, the system, because of its setup, can handle many sizes of tests separately and concurrently.

Pressure-cabin Problems.—Another new phase of testing that has only in the last year become of much interest to the test engineer is the field of pressure-cabin research. These investigations cover a very wide range on a pressurized airplane—all the way from fuselages to Plexiglas canopies, and from cable-gland seals to airtight doors. The principles used in testing all these structures are similar; the pressure tightness of each item under internal pressures of 6 to 9 lb. per sq. in. must be proved adequate. The sealing compound or synthetic rubber used in making the seal may be much affected by low temperatures, flexure, and vibration. It is therefore often necessary to subject the pressurized specimen to repeated loads or refrigerated conditions.

The structural instability and "breathing action" of a portion of an airplane, when subjected to pressure, may be the criterion of a design, as was the one-half-scale replica of a fuselage section shown in Fig. 18. A pressure test will soon show weak points of such a structure.

Sound Tests.—The jobs of establishing how noisy or quiet an airplane is in flight, the sound intensities of factory equipment, or the major sound frequencies that are the most troublesome in a given situation, with recommendations for improvements, become an everyday problem for a sound test engineer. Sound meters and analyzers are now available to aid the human ear judge the intensities of sound. The author is shown in Fig. 28 in the act of checking the sound intensity near a bumping hammer with a portable sound-level meter. This hammer was subsequently silenced by the use of the proper acoustical treatment.

The same portable meter or its companion sound analyzer is used on airplanes in flight to check on guaranteed sound-level intensities. Recording sound analyzers, although much more expensive than the more simple portable types, are being more generally used in aircraft flight testing, to save costly test flight time and for greater accuracy of results.

Vibration Tests.—Inasmuch as an airplane travels in a three-dimensional medium, is air-borne on a variable air structure,

and is built as light as is practical, it is also subjected to vibrations, shocks, flutter, and similar disturbances in its component parts owing to its very lightness and flexibility.

Again the test engineer, this time as a vibration expert, must inspect every new airplane model, make sufficient vibration tests of the airplane on the ground, and write reports to prove the

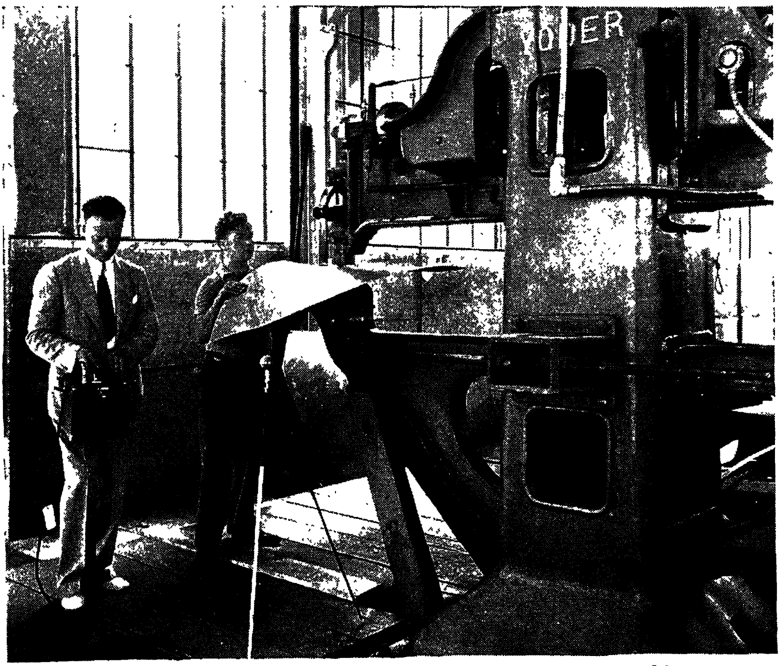


FIG. 28.—Checking sound intensity of metal bumping machine.

adequacy of the airplane structure to stand the initial dive pull-outs and demonstration tests at high speed.

This field of vibration and flutter in aircraft structures, in flight and on the ground, is a new one. No test engineer, no matter how experienced he may be, knows all the answers. It is becoming increasingly evident in test engineering, especially in the fields of vibration, sound, and electricity (radio), that test engineers should be trained as specialists in these lines for maximum efficiency of test-data interpretation.

To save valuable flight test time, many vibration tests are duplicated on the ground. In Fig. 29 is shown a test assembly

of an engine mount. This welded steel mount supports a 2,000-lb. mass of lead, on conventional vibration-isolation pads, with the correct mass distribution as represented by the radial engine and its accessories. Through this lead mass extends a shaft, mounted on ball bearings, rotating an eccentric mass at the outer end by means of a belt drive from a variable-speed electric motor at the inner end. This test rig shook the engine mount for hundreds of hours with amplitudes greater than the average vibration to be expected in an aircraft in flight.

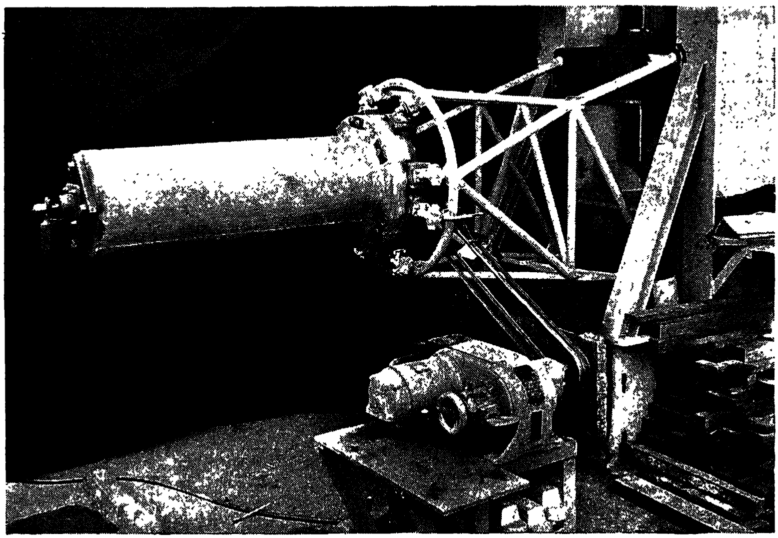


FIG. 29.—Vibration test of an engine mount.

Inasmuch as each test assembly, like the above, is special and applicable to only one particular test condition and situation, it is again evident that test engineers must be practical and capable of responsible and independent action in any test project that is assigned them.

Control-system Tests.—No matter how fragmentary are the special tests demanded of an airplane, it is customary to check the control-system assembly thoroughly after installation in a new plane. This comprises the application of proof loads to the pilot's control wheel and rudder pedals and to the cable system back to each control surface to determine the strength and rigidity of the control brackets, control arms, etc.

Control-system tests are so standardized that a test engineer should be able to check a new ship in a day's time. It is conventional to retest an airplane's control system if any of the control cables are rerouted during a redesign, since the added control brackets, fair-leads, etc., are sometimes the most troublesome owing to lack of rigidity.

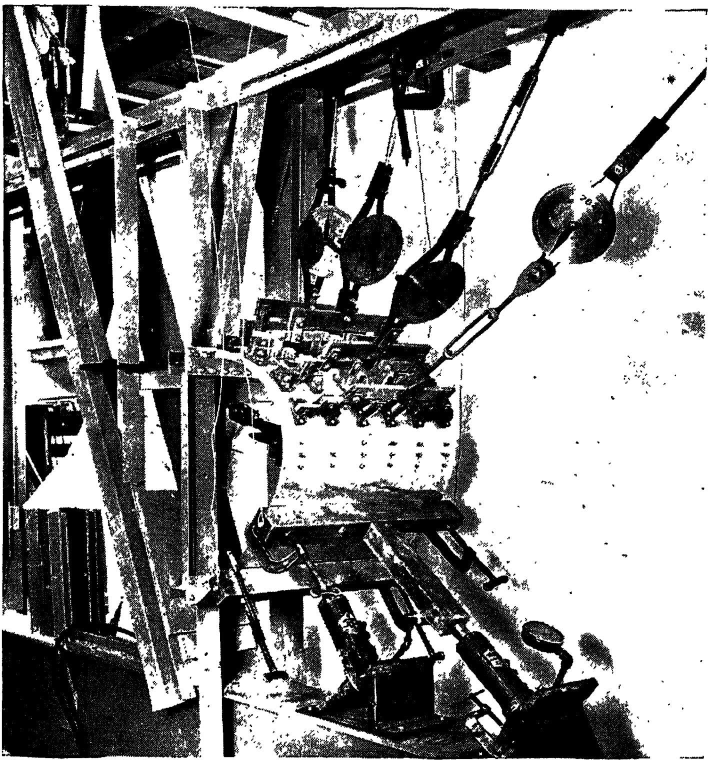


FIG. 30.—Static test of wing leading-edge specimen.

Special Structural Tests.—Few fields of engineering give an engineer more freedom of design and expression of individual ideas and opinions than does test engineering. And in the various test phases in the engineering test laboratory, probably the structural test engineer has the best opportunity to express his individuality in solving new problems.

Take, for example, the case of the leading-edge destruction test presented to one test engineer in which the suction load over

the upper surface had to be applied simultaneously with the dynamic pressure loading on the nose and lower surface. The conventional method, used some years ago, was to apply a sand-bag pile on the lower surface of the inverted leading-edge section to represent the total load, the suction load that should be placed on the opposite surface being conveniently forgotten. Today, however, the test engineer attacks this problem honestly, placing the positive and negative loads on the test specimen where they

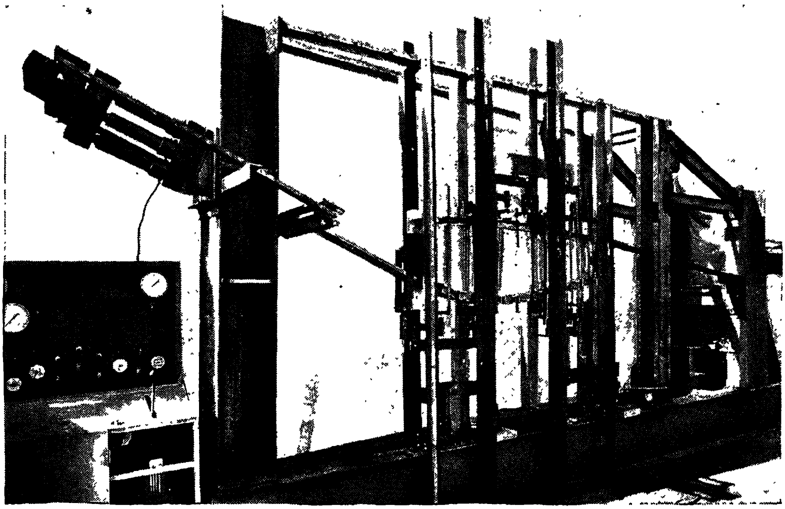


Fig. 31.—Static test of wing bulkhead specimen.

occur on the wing in flight, as shown in Fig. 30. This method, in which he cleverly uses whippletree levers, turnbuckles, and dynamometers at various angles to apply the suction loads on the upper surface and hydraulic jacks to apply the dynamic pressure loads, shows again that the test engineer must be master of the test apparatus.

Another common example of the use of levers, hydraulic rams, and dynamometers is often seen in the engineering test laboratory setups for the testing of wing bulkheads or hull belt frames. Figure 31 shows a typical test of a large wing bulkhead under a distributed air loading, crushing loads, spar end moments, and upper and lower skin shear loads. Only by the simultaneous application of these actual flight structural loads to such a bulk-head can the true strength and point of failure be determined.

It will be noted in these examples that apparently little thought has been given to the cleanliness and appearance of the test jigs. The test jigs are utilitarian only, to be built up and torn down with each test, if necessary, and the test engineers are encouraged to think of simplicity, accessibility, and duplication of test conditions rather than of showmanship. The basic test jigs of Figs. 30 and 31 may be used as a foundation for dozens of major tests, by changing lateral guides, load points, lever lengths, etc., and then the jig has paid for itself and may be scrapped to make room for a new jig. This is a sign of test-engineering progress.

CONCLUSION

The previous pages have barely scratched the surface of test and research activities in an average aircraft company or the myriad duties of a good test engineer. Many test fields such as X-ray inspection, stress detection by brittle lacquer coatings, crack detection by magnetic inspection, and vibration tests in flight have not even been touched. Many of these subjects have been well discussed in the works listed under References.

The author wishes to make one plea to his readers who may be interested in test engineering: Do not be satisfied with the formal education with which you enter the aircraft industry. Keep learning! The industry, and especially the test-engineering portion of it, is moving too fast for any one test engineer to know all the answers. This is a cooperative group, each man contributing his share, to the end that test engineering may be some day as well known and admired as any other branch of engineering. Remember that "one good test is worth a thousand expert opinions."

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APPENDIX

TABLE I.—METALLIC AIRCRAFT MATERIALS

Material			Form	Cost (approximately)		Specific gravity (D)	Weight, lb. per cu. in.	Tension						Elongation per cent in 2 in.	Shear			Fatigue limit
Description	Specifications							Ultimate yield			Modulus of elasticity				Ultimate		Modulus of rigidity G	
	U.S. Army	U.S. Navy		Per lb.	Per cu. in.			T	T/D	Y	Y/D	E	E/D		S	S/D		
Aluminum alloys:																		
17ST	WW-T-786	44-T-21b	Tube	$1.60		2.79	0.101	60	21.5	37	13.3	10.3	3.7	20	36	12.9	3.8	15
24ST	11066	47-A-10	Sheet	0.60	$0.06	2.77	0.100	68	24.6	44	15.9	10.3	3.7	19	41	14.8	3.8	18
24ST-Alc	11067-II	47-A-8	Sheet	0.60	0.06	2.77	0.100	62	22.5	41	14.8	10.3	3.7	18	40	14.4	3.8	
24SRT	11067-III	47-A-10	Sheet	0.70	0.07	2.77	0.100	70	25.3	55	19.9	10.3	3.7	13	42	15.2	3.8	
25ST	57-153	46-A-7	Bar			2.79	0.101	55	19.7	30	10.8	10.3	3.7	16	35	12.6	3.8	15
14ST	57-153	M-277B	Bar	1.00	0.10	2.79	0.101	65	23.3	50	18.0	10.3	3.7	10	45	16.1	3.8	16
195-T4		46Ale-4	Casting	1.35	0.13	2.77	0.100	31	11.2	16	5.8	10.3	3.7	8.5	24	8.7	3.8	6
356-T4		46Ale-3	Casting	1.35	0.13	2.65	0.096	28	10.6	16	6.1	10.3	3.9	6	22	8.3	3.8	
220-T4		M-186	Casting	1.35	0.12	2.56	0.092	45	17.6	25	9.8	10.3	4.0	14	33	12.9	3.8	7
Magnesium alloys:																		
M alloy	(AM3S)	M-314-11	Sheet	1.00	0.04	1.76	0.064	35	19.9	27	15.4	6.5	3.7	9				6.5
E alloy			Sheet	1.20		1.79	0.065	45	25.2	34	19.0	6.5	3.65	9				
J alloy	(AM57S)	M-314b-8	Extrusion			1.80	0.065	43	24.0	30	16.7	6.5	3.62	17	20	11.1		17
H alloy	57-74-IC	M-112AL4	Casting	2.00	0.13	1.83	0.066	38	20.8	18	9.8	6.5	3.55	5	18	9.8		10
Copper alloys:																		
Naval brass	57-162	46-B-6	Bar	0.30	0.09	8.23	0.30	67	8.1	45	5.5	15	1.82	22				
Aluminum bronze	QQ-B-666	46-B-17b	Bar	0.50	0.14	7.8	0.28	75	9.6	37	4.7	15	1.92	20				
Manganese bronze	QQ-B-721	46-B-15c	Bar	0.30	0.08	7.8	0.28	85	10.9	60	7.7	16	2.05	5				
Lumen No. 20			Bar	0.60	0.17	7.7	0.28	110	14.3	70	9.1	16	2.1	12				
Cu-Be (heat-treated)			Sheet	1.30	0.39	8.23	0.30	175	21.2	134	16.2	18.9	2.3	6.3	95	11.4	7.0	
Steel alloys:																		
1025	57-107-9B	46-S-22	Bar			7.8	0.28	55	7.1	136	4.6	28	3.6	22			10	25
2330	57-107-17b	46-S-21b	Bar	0.15	0.04	7.8	0.28	125	16.0	100	12.8	29	3.7	17			11	65
X4130	57-107-19b	46-S-23E	Bar	0.15	0.04	7.8	0.28	150	19.2	135	17.3	29	3.7	18	100	12.8	11	78
4345	11062	46-S-28	Sheet			7.8	0.28	230	29.5	220	28.2	30	3.9	4			11	95
Stainless-steel alloys:																		
18-8	57-136-9	47-S-19	Sheet	0.70	0.19	7.8	0.28	80	10.2	35	4.5	26	3.3	40	70	9.0		30
18-8	11068	47S21½H	Sheet	0.70	0.19	7.8	0.28	150	19.1	110	14.0	26	3.3	10	100	12.8		55
18-8	10079	46S18-1C	Bar	0.55	0.15	7.8	0.28	120	15.3	60	7.7	30	3.9	15				
18-8	10079	46S18-7E	Bar	0.55	0.15	7.8	0.28	100	12.8	50	6.4	29	3.7	28				
16-2		M-286	Bar	0.50	0.14	7.8	0.28	175	22.4	135	17.2	30	3.9	13				
Nickel alloys:																		
Inconel	57174	47N1a	Sheet			8.55	0.31	125	14.5	100	11.6	31.5	3.7	7			10.5	
Monel			Sheet	0.80	0.26	8.9	0.32	100	11.2	90	10.1	25.5	2.9	8			9.2	
K Monel (C)			Bar	0.80	0.25	8.6	0.31	160	18.5	120	13.9	25.5	2.95	20			9.2	
Be-Ni (heat-treated and rolled)			Bar			8.1	0.29	260	32.0	213	26.2	27	3.32	8				

TABLE II.—NONMETALLIC AIRCRAFT MATERIALS

Material	Specific gravity D	Moisture absorption*		Tension				Temperature to soften, degrees Centigrade	Compression, ultimate		Shear, ultimate		Source
				Ultimate		Modulus of elasticity							
		Percentage	Period	T	T/D	E	E/D		C	C/D	S	S/D	
Synthetic resins:													
Paper filler	1.37	0.9	24 hr.	15.3	11.2	1.61	1.18	None	21.7	15.5	8.5	6.2	*N.A.C.A. Tech. Notes*, No. 694
Canvas filler	1.30	0.4	24 hr.	10.2	7.8	1.80	1.39	None	18.3	14.1	10.2	7.8	*N.A.C.A. Tech. Notes*, No. 694
Linen filler	1.30	0.2	24 hr.	10.0	7.7	1.43	1.10	None	19.6	15.0	11.5	8.8	*N.A.C.A. Tech. Notes*, No. 694
Phenolic resins:													
Cotton flock	1.37			6.8	5.2			None	27.0	20.6			*N.A.C.A. Tech. Notes*, No. 628
Wood flour	1.37			7.5	5.5			None	30.0	22.1			*N.A.C.A. Tech. Notes*, No. 628
Fabric	1.37			10.0	7.2			None	40.0	29.0			*N.A.C.A. Tech. Notes*, No. 628
Paper	1.37	0.8	24 hr.	19.0	14.0	1.20	0.88	None	30.0	22.0			*N.A.C.A. Tech. Notes*, No. 628
Urea resin, paper	1.53	1.0	7 days	10.0	6.5			None	30.0	19.6			*British Plastics*
Duramold:													
Type I, optimum	0.7	Average 1.0	7 weeks	25.7	36.5	2.15	3.06	None	13.9				*Inter Avia*
Type I, 90 deg. to optimum	0.7	Average 1.0	7 weeks	4.7	6.7	0.50	0.71	None	7.7				*Inter Avia*, June 20, 1939
Type IV, optimum	0.7	Average 1.0	7 weeks	16.7	23.8	1.43	2.04	None	11.2				*Inter Avia*, June 20, 1939
Type IV, 90 deg. to optimum	0.7	Average 1.0	7 weeks	13.9	20.0	1.21	1.73	None	10.4				*Inter Avia*, June 20, 1939
Jicwood	1.28	2.0	24 hr.	27.5	21.5	4.50	3.51		17.4	13.6	4.9	3.8	*Aeroplane*, October, 1937
Compound 1840	1.26	6.2	24 hr.	29.6	23.5	3.50	2.65		21.2	16.9	5.3	4.2	*N.A.C.A. Tech. Notes*, No. 694
Birch-reinforced resin	1.27			27.7	21.8	3.40	2.68		22.8	18.0			*Modern Plastics*, September, 1938
Aerolite, cord	1.34			25.0	18.7	2.0	1.49		27.0	20.1	5.8	4.3	*R.A.S.*, January, 1937
Aerolite, Gordon	1.43			45.0	31.5	6.0	4.20		24.0	16.8	5.0	3.5	*R.A.S.*, January, 1937
Felt-base resin	1.38			28.0	20.3	2.77	2.01		25.0	18.1	9.0	6.5	*Aeroplane*, Nov. 9, 1938
Cellulose nitrate	1.50	3.0	24 hr.	8.0	5.3			85	15.0	10.0			Boonton *Plastics*
Cellulose acetate	1.30	2.0	24 hr.	4.6	3.5	0.3	0.23	70	14.0	10.8			Boonton *Plastics*
Methyl methacrylate	1.200	0.5	7 days	10.0	8.3	0.6	0.50	135	8.0	6.7			Boonton *Plastics*
Vinyl resin	1.35	0.1	24 hr.	9.0	6.6	0.4	0.30	70					Boonton *Plastics*
Plate glass	2.5	0		3.0	1.2			1100	20.0	8.0			
Safety glass	2.35	0		3.0	1.2			1100†	20.0				
Spruce	0.40	12	24 hr.	9.0	22.5	1.3	3.25		5.0	12.5	0.75	1.88	*N.A.C.A. Tech. Notes*, No. 296
Birch	0.68	12	24 hr.	15.0	22.1	1.8	2.65		7.3	10.7	1.3	1.91	*N.A.C.A. Tech. Notes*, No. 296
Mahogany	0.51	12	24 hr.	11.0	21.6	1.25	2.45		6.5	12.7	0.86	1.69	*N.A.C.A. Tech. Notes*, No. 296

* Complete immersion.
† Plastic core softens at 70°C.

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